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The Theory of Heat-Engines

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INCLUDING THE ACTION OF MUSCLES

BY

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PREFACE

In my book *Gases and Liquids*, published in 1928, two chapters are devoted to the theory of heat-engines and muscular contraction. Some explanation may therefore be expected of this further publication on the subject.

The explanation is twofold. In the first place, I had meanwhile come to see clearly that in the last chapter of the book I had failed to do justice to the possibilities of the steam-engine. In the second place, it had also become evident to me that the main new points in my treatment of the theory of heat-engines could be stated a good deal more simply and shortly, while the theory of muscles as heat-engines required expansion. For both engineers and physiologists, as well as for other readers, it would probably also be convenient to have the reasoning in a single short book.

The influence of mere scientific authority is so very potent that many persons who hear of the conclusions to which a careful consideration of the heat-engine has led me will be apt to

reject them at once as "unsound." Thus the author of a well-written review in *The Engineer* of my previous book says, with reference to my criticism of the fundamental conceptions of Carnot and Kelvin as to reversible heat-engines, that of course it is admitted that a reversible heat-engine working between the temperatures of a source and condenser is only an ideal conception. But if, as I show, it is not only an ideal conception, but also an impossible one, which neither corresponds with the phenomena in an actual heat-engine nor with the nature of heat itself, the mathematical elaboration of the conception has become quite unmeaning. In deference to authority, engineers and physiologists have for more than half a century endeavoured to apply this elaboration to actual heat-engines and contracting muscles; but the application, as it seems to me, is quite clearly impossible, so that the elaboration is nothing but a useless burden. As a mere mathematical exercise the elaboration is interesting and exact; but it does not apply to heat-engines.

Both the solid structure and working substance of heat-engines are molecular; and the engine itself is a molecular mechanism actuated by the chaotic form of molecular kinetic energy which we call heat. The necessary consequence

of this is that no heat-engine can be anything approaching to reversible in the manner imagined by Carnot; and Kelvin's idea that absolute temperature could be defined in terms of the thermal efficiency of a Carnot engine working reversibly between the temperatures of a source and condenser must be abandoned as being inconsistent with the nature of heat.

I have endeavoured in this book to give a theoretical account of heat-engines as they actually exist or may exist, taking into consideration essential facts well known empirically to engineers. For the conceptions of Carnot and Kelvin as to the possible thermal efficiency of heat-engines there is no longer any place.

If the conclusions reached in this book as to the potential thermal efficiency of steam-engines, as compared with that of internal-combustion engines, are correct, it becomes evident that coal in the solid state is much more valuable as a source of power than has yet been realised, and that its capacity for generating mechanical or electrical power is as great as that of liquid or gaseous fuel of corresponding calorific value. For countries which, like the British Empire, possess large supplies of coal, but little oil, this is a matter of very great importance. We can also, I think, look forward to a great further

development of the steam-engine burning either solid coal or crude heavy oil as its fuel, and of both the direct and the electrical distribution of the power so generated. Most of the steam-engines and boilers at present in use are quite antiquated in design.

The mechanism by which a muscle produces mechanical power seems at first to be very different, whatever its nature, from that by which an artificial heat-engine produces power. But, if the reasoning in this book is correct, both are heat-engines; and we cannot understand the muscular heat-engine without understanding the artificial one, though the driving pressure in a muscle is not produced by rise of temperature. For this reason muscular contraction, as well as the action of artificial heat-engines, is treated in the book. The discovery and application of scientific principles is common to many of the branches of science. Both physics and chemistry have owed much to investigators who were primarily biologists, and *vice versa*. We have only to consider the fact that the very useful conception of energy in the modern sense originated with a country doctor called Mayer and an army-surgeon called Helmholtz, or that Mayow, who first saw the connection between consumption of what we now call oxygen and

the development of power by muscles and explosives (though ordinary heat-engines were not then invented), was also a doctor.

It thus seems unnecessary for me to apologise in any way for the fact that muscular contraction is treated in this book along with the action of artificial heat-engines, or for the fact that I am primarily a biologist and not a physicist.

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CHAPTER I

THE CONCEPTIONS OF CARNOT AND KELVIN

WHETHER we consider internal-combustion engines, or steam-engines, or muscles, the accepted theory of their action, as I shall endeavour to show below, is at present far from satisfactory, though excellent descriptions exist of their structure, the results given by them, and the various improvements which with growing experience have been added to artificially constructed heat-engines. In certain respects we are, I think, no further forward on the theoretical side than at the middle of last century, when it was first realised that heat is molecular kinetic energy; and the defects on the theoretical side seem to me to have had a very unfavourable influence on the practical development of heat-engines.

As Carnot pointed out in 1824, a heat-engine works in a cycle, during which heat is communicated to a working substance, through the expansion of which work is obtained in ordinary heat-engines, and which is returned to its original

state or the equivalent of this state at the end of each cycle, with unavoidable throwing away of much work and heat in the return. Since, however, more mechanical energy is obtained in the expansion than is wasted in the compression stage, there is a net gain of directed mechanical energy during the cycle, this gain being due to the fact that the working substance is hotter during the expansion.

The existing theoretical account of a heat-engine is based, partly on Carnot's demonstration that it works in a cycle, leaving everything belonging to the engine in the same state as at the beginning of the cycle; partly on his demonstration (dependent on the principle that mechanical energy or heat cannot be created) that if a heat-engine, when driven backwards by the same stages, and restoring the original state at the beginning of the cycle, absorbed no more mechanical energy than was gained when it worked forwards, a more efficient method of working with the same stages would be impossible; and partly on the later conception that heat is molecular kinetic energy and is converted during the expansion into mechanical energy, some of which is reconverted into heat during the compression stage.

A reversible mode of working (in Carnot's

sense) has thus come to be regarded as the ideally efficient mode of working for a given cycle; but it will be evident that whether or not a heat-engine is completely reversible, if it converts into mechanical energy during expansion all the heat supplied to it, and reconverts into heat during compression no more heat than is reconverted into mechanical energy in the backward working by the same path, the engine will be just as perfect as a completely reversible engine, since all the heat-energy has been converted into mechanical energy, minus the minimum mechanical energy lost in recompression of the working substance by the same path.

In accordance with Carnot's conception of an ordinary heat-engine, the proportion of heat-energy converted into mechanical energy must depend on the difference in temperature between the working substance in expansion and compression; and since, as was first pointed out by Waterston in 1845, both the temperature and pressure of a gas are, other things being equal, a measure of molecular kinetic energy, it seemed natural to conclude, as Kelvin did before he even knew that heat is energy, that the thermal efficiency, or proportion of mechanical energy obtained to heat-energy supplied, must

be dependent in any heat-engine on the difference in absolute temperature between the working substance in expansion and in compression. When, however, the working substance changes its state during the cycle, as in a steam-engine or muscle, this conclusion no longer holds, as will be shown below.

In the cycle of the engine which Carnot imagined, a certain volume of air at a certain pressure in a cylinder, and at the temperature of a condenser, is supposed to be first further compressed adiabatically by the action of a flywheel already in motion, till the temperature of the air reaches that of a source of heat, which is then applied to the bottom of the cylinder. The air is then supposed to be allowed to expand isothermally at the temperature of the source of heat, absorbing heat from it, and doing work on the flywheel and to the outside. When the expansion has gone a certain way the source of heat is removed, and the air is supposed to be allowed to expand further adiabatically, doing more work, till its temperature falls to that of the condenser, with which the bottom of the cylinder is then brought into contact. The air is then, by the action of the flywheel, compressed isothermally to its original volume, its temperature being supposed to remain steady at the

temperature of the condenser, which absorbs the heat liberated.

This completes the supposed cycle of the engine. For the first stage just as much mechanical energy is theoretically applied as is regained during the stage of expansion in the absence of the source of heat; but since the air during expansion in presence of the source is at a higher temperature than during compression in presence of the condenser, more mechanical energy is gained during the expansion than is lost during the compression, so that the engine can do net external work. And since the number of molecules is the same during compression as during expansion, the thermal efficiency is represented by the ratio of the difference in absolute temperature between condenser and source to the absolute temperature of the source, or by $\frac{T - T_1}{T}$ if T is the absolute temperature of the source, and T_1 that of the condenser. The engine, as described, would be completely reversible in Carnot's sense, apart from losses due to friction. It is assumed, however, that the air loses no heat except through the doing of work or directly to the condenser, and gains no heat except through work done upon it, and directly from the source of heat.

Fig. 1 represents approximately the changes in volume and pressure which would take place

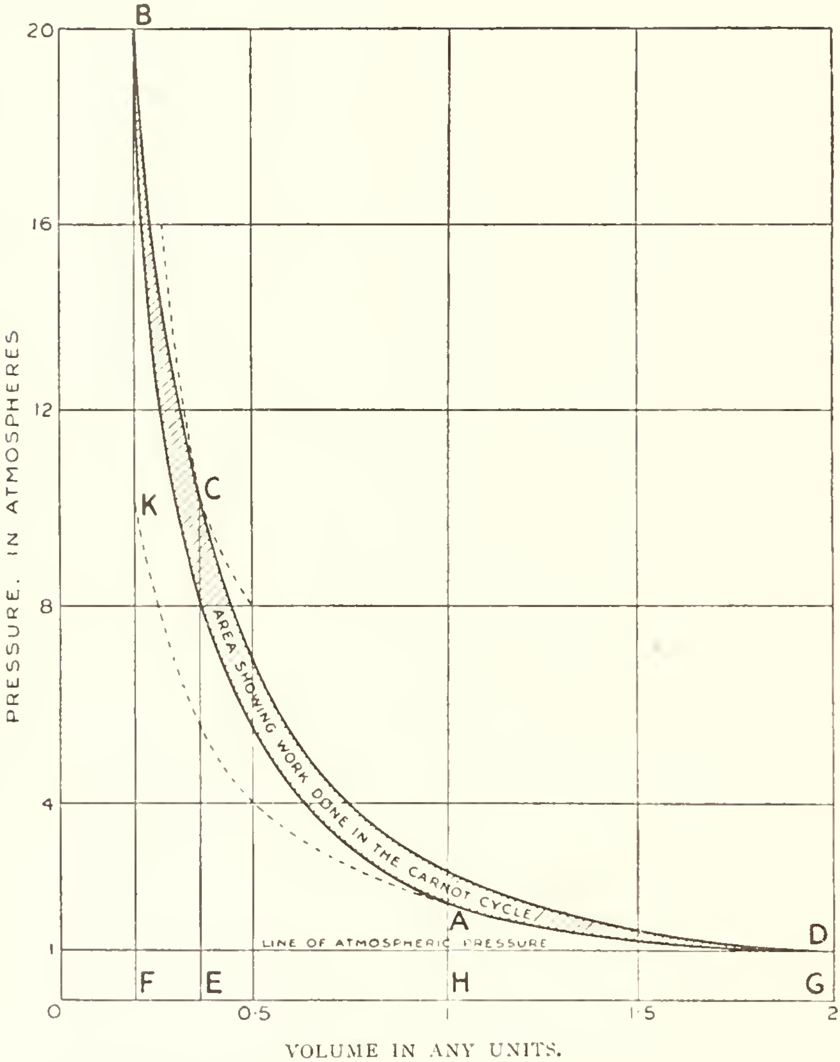

FIG. 1.—Cycle as imagined by Carnot, with Lower Absolute Temperature 50 per cent. below Upper.

during the cycle of Carnot's ideal engine, assuming that the absolute temperature of

isothermal expansion in presence of the source of heat was double the absolute temperature of isothermal compression in presence of the condenser. The long-drawn-out adiabatic expansion (CD) and adiabatic compression (AB) are indicated in the figure; and it may be remarked that the schematic figures usually given of a Carnot cycle are extremely misleading. In the lines representing adiabatic compression or expansion pv^{γ} ought to be constant.

It has often been assumed (for instance by Clerk Maxwell[1]) that the conditions imagined by Carnot would be nearly fulfilled if the cylinder were well heat-insulated. Actually, however, they are impossible of fulfilment, because the metal, or other substance composing the walls, consists of molecules, and therefore takes up heat when colder than the contained air during the last part of compression and most of expansion, and when hotter than this air during the last part of expansion and nearly all of compression, gives off to it heat. Moreover, heat cannot flow from the source of heat into the contained air unless the source is at a higher temperature, and cannot flow into the condenser from this air unless the former is at a lower temperature. If, however, the Carnot engine worked very slowly, this

[1] See Clerk Maxwell's *Theory of Heat*, Chapter VIII.

objection would scarcely apply, provided that the first objection could be overcome.

But if the Carnot engine works very slowly a great deal of heat will have time to leak into the walls and to a greater or less extent through them to the outside while their temperature is below that of the contained air, and to leak out again into the contained air while the temperature of the walls is higher. However effectively the cylinder is heat-insulated this leakage will by itself bring the difference in temperature between the enclosed air during expansion while the bottom of the cylinder is in contact with the source, and the same air during compression while the bottom is in contact with the condenser, to a mere fraction of what it would otherwise be; and much heat will pass uselessly into the condenser. If, on the other hand, the engine is allowed to work fast enough, there will be so little time for heat to pass from the source to take the place of the heat which disappears rapidly owing to the work done in expansion, and so little time for the heat formed during the rapid compression to escape into the condenser, that from these causes the difference in temperature between the air during expansion in contact with the source, and compression in contact with the condenser will become small, and tend to disappear

completely. If, indeed, the engine was driven fast enough by externally applied force, it would act as a brake.

It was pointed out by Kelvin that if T was the absolute temperature of the source of heat, and T_1 the absolute temperature of the condenser, the thermal efficiency of an engine working as Carnot imagined would, if expressed as a fraction of unity, be practically $\frac{T - T_1}{T}$. Indeed, Kelvin based his definition of absolute temperature on the thermal efficiency of such an altogether ideal engine, instead of, as Waterston did, on the dynamical theory of heat and temperature as applied to a world of molecules; and Kelvin's definition of absolute temperature has survived till the present day.

Now, by no possibility can the conditions imagined by Carnot be even approximately fulfilled. In addition to the heat which would necessarily be lost in the condenser owing to work done on the air during compression, an unlimited additional amount of heat would be wasted by leakage of heat into the walls, and thence to the condenser or outside, if the engine were working slowly enough. The net work done per cycle would also be far less than Kelvin calculated, since, owing to continual leakage of

heat into and out of the walls, the temperatures of expansion and compression would be far closer together than he calculated. If, moreover, the resistance to the engine was so diminished as to permit of its working very fast, thus greatly curtailing the escape of heat per cycle into the walls, the difference between the temperatures of expansion and compression would become extremely small, so that very little net work would be done, while much extra heat, produced in compression, would pass uselessly into the condenser. Evidently, also, the mere temperatures of source and condenser are of no direct importance in determining the net work done per cycle. The relative temperatures of the enclosed air in expansion and compression are what matters.

The engine is also hopelessly irreversible in Carnot's sense. The smallness of the power gained in the forward action makes it quite insufficient to restore to the source the heat which it had lost. Indeed, no heat at all will be returned to the source, since the temperature of the air during compression in the reversed action will be below that of the source.

If the engine was working slowly enough the loss of heat from leakage into the walls, and thence to the condenser, or direct to the outside,

would be so enormous in relation to the heat converted into mechanical energy, that the thermal efficiency would be practically zero. On the other hand, if the engine were given no work in expansion, and there was no friction, it would run so fast that the temperatures of compression and expansion would be equal, the leakage through the walls to the condenser being zero, but a very large extra amount of heat, formed in consequence of the velocity of compression, passing into the condenser without any net work being done. It is thus evident that there must be an intermediate rate, at which loss of heat per cycle by leakage is reduced as far as possible without at the same time increasing to a greater extent the loss of heat owing to increasing velocity. At this point the thermal efficiency will be at its highest. It is also evident that there must be a velocity at which the loss of heat from leakage towards the condenser and outside is equal to the extra heat lost owing to the velocity.

Let us suppose that this velocity has been reached. If, now, we increase the velocity, which we can only do by diminishing the resistance, the proportion of the heat absorbed which leaks into the walls will be correspondingly diminished, and the proportion converted into mechanical

energy during expansion increased.[1] This latter proportion can only increase directly as the velocity, and not as the square of the velocity, since the resistance is diminished in proportion to the increased velocity. But the negative work done on the enclosed air during compression will increase as the square of the increased velocity, the loss of heat to the condenser increasing correspondingly. The thermal efficiency, which depends on the net work done per unit of heat absorbed, will therefore diminish. If, on the other hand, we diminish the velocity, the thermal efficiency will also diminish, since the work done during expansion in relation to the heat absorbed will diminish in direct proportion to the velocity, regarding the original velocity as unity, while the work done in compression will only diminish in proportion to the square of the velocity, which is now under unity, and therefore produces a smaller diminution in work done in proportion to heat absorbed than the diminution in work done during expansion per unit of heat absorbed. Thus maximum efficiency is reached when the loss of heat by leakage into the walls is equal to the extra loss owing to the velocity of compression.

[1] In actual fact the proportion which leaks will be diminished somewhat more than in proportion to the increased velocity, since the temperatures of expansion and compression will have come closer together.

It also follows that when the combined loss, owing to leakage and to extra heat produced in compression, of heat absorbed is equal to that converted into net mechanical energy, maximal thermal efficiency is reached. For if the velocity is increased beyond this point the loss from increased velocity of compression will be greater than the gain from diminished leakage: while if the velocity is diminished the gain from diminished loss in compression will be, for the reason already stated, less than the loss from increased leakage. Hence when maximum efficiency is reached the proportion converted into net mechanical energy of the heat absorbed is only half of that which would be converted but for leakage and velocity of compression. Half the loss is due to leakage, and half to velocity of compression.

It follows that the maximal thermal efficiency is just half what it would be if, with the actual temperatures of isothermal expansion and compression, the engine were reversible in the modified sense that the actual temperatures of expansion and compression were restored in the backward action ; and even if the condenser temperature were absolute zero, and the temperature of the source were indefinitely high, the maximum theoretical efficiency could not exceed 50 per cent., even if there were no loss from friction.

This theorem, as we shall see, is applicable, *mutatis mutandis*, to all heat-engines, and is of fundamental importance in the theory of heat-engines.[1] It enables us to give an extended interpretation to the second law of thermodynamics if we take this law as the statement that by means of any apparatus which returns to the same state afterwards, it is not only impossible to obtain net mechanical energy from the heat in other bodies of lower or equal temperature, but also impossible to convert into mechanical energy more than half the heat we could convert if we could work the apparatus backwards by applying the same amount of work as was obtained in the forward action.

The reason why this is so is simply that heat, unlike other forms of energy, is, so far as our ordinary perception of it goes, chaotic, so that it tends to spread itself out evenly among surrounding molecules, including the molecules of the apparatus itself. The so-called second law of thermodynamics, however imperfectly it may be stated, is not a primary physical law, but follows as a corollary from the dynamical conception of heat and temperature as formulated by

[1] The same theorem is also stated in my book *Gases and Liquids*, but in a less simple form involving algebraical expressions, and not altogether correctly.

Waterston in 1845 in the now well-known paper[1] which the Royal Society referees so unfortunately rejected, since they believed, in common with the mathematical physicists of the time, that heat is an indestructible substance.

We can convert applied heat wholly, or almost wholly, into mechanical energy, as, for instance, when, by means of contracted openings, we convert the whole of the extra heat in steam or compressed air into energy of its own bodily motion in a turbine. But if we use the turbine and its working substance as a heat-engine which returns its working substance to the same state in a cycle, we cannot, as will be shown below, obtain from it more than half the mechanical energy which we could have obtained if the working process had been of such a nature that it could be reversed by applying the same power in the opposite direction as was obtained in the forward action. We inevitably waste most of the heat-energy applied in any heat-engine, whatever the temperatures of the source of heat and condenser may be.

If we call T the absolute temperature of actual isothermal expansion in a Carnot engine, and T_1 that of its isothermal compression, the

[1] See Waterston's *Collected Papers*, p. 207 (Oliver & Boyd, 1928).

maximal theoretical thermal efficiency is $\frac{T - T_1}{2T}$, when the efficiency is expressed as a fraction of unity. If, however, we took T and T_1 as the temperatures of the source and condenser, the theoretical maximal efficiency would, in a Carnot engine, only be a small fraction of $\frac{T - T_1}{2T}$, since the difference between the actual temperatures of isothermal expansion and compression, with the engine working at its optimum rate, would only be a small fraction of $T - T_1$.

It is evident that it would be quite useless to attempt to prolong the compression till the temperature of the source, or any temperature higher than that of isothermal expansion, was reached, or prolong the expansion till that of the condenser, or any temperature lower than that of isothermal compression, was reached. On account of heat leakage into or out of the walls, these points would practically never be reached with the engine running at its optimum speed. Nor, in so far as they tended to be reached, would there be any increase in thermal efficiency. The whole cycle, so far as it is profitable, will be much shorter.

If we increased the velocity of the Carnot engine beyond the velocity which gave maximum

thermal efficiency, it is evident that at first the horse-power would not diminish with the thermal efficiency: for though less work would be done per cycle, this would be counter-balanced by the increased number of cycles per unit of time, and by leakage being diminished owing to the temperatures of expansion and compression coming nearer. With further progressive increase in velocity horse-power and thermal efficiency would reach zero together.

If the Carnot engine was already working at the velocity giving maximum thermal efficiency, a comparatively small relative increase in this speed would greatly diminish the thermal efficiency, owing to the rapid increase of loss in compression. If the engine was by some means made to run at a little more than as fast again as its optimum speed, it would already be acting as a brake; and any heat-engine can be made to act as a brake in this way.

On the other hand, we could diminish considerably the relative velocity without diminishing to more than a moderate extent the thermal efficiency, since the net work done per cycle would at first be increasing considerably, though the leakage of heat would be increasing more rapidly. With further reduction in velocity the leakage of heat would increase in proportion as

the relative velocity diminished, and the work done per cycle would practically cease to increase. Thus the efficiency would only approximate gradually to zero. In this respect the Carnot engine, as we shall see, resembles the steam-engine, but not the internal-combustion engine.

No actual heat-engine works like a Carnot engine. This is not because heat-engines are not reversible in Carnot's sense, but partly because the temperature of the working substance is raised by compression, thus necessitating a very long stroke for the work done, and consequent extravagant size of cylinder and loss by leakage of heat and friction: partly also because the method of communicating heat to the working substance during expansion, and removing heat from it during compression, is extremely slow, so that the bad effects of leakage and of the inefficient condenser are overwhelming. Whether a Carnot engine could ever be made so free from friction that it could complete a cycle without being pushed seems extremely doubtful; and the Carnot engine may be regarded as the very model of an ineffective and wasteful heat-engine, though just for that reason it is a very instructive model to consider. In all ordinary heat-engines the essential rise and maintenance of temperature is brought about

simply by the *rapid* communication of heat to the working substance; and the measure of thermal efficiency in any heat-engine is the proportion of energy obtained in the mechanical form from the heat-energy applied, whether or not the driving pressure is due merely to rise of temperature.

On reading Carnot's description of his ideal reversible engine it is quite evident that he had not realised the significance of the fact that heat is something which is constantly leaking in all directions to and from the structure of the engine, as well as to the outside. He also did not realise the difference between a gas-engine and a steam-engine. In a steam-engine working at an ordinary rate we can have, if we pay for it in heat, isothermal expansion at practically the temperature of the boiler, and isothermal compression at that of the condenser; but it is impossible in a gas-engine to have the temperatures of expansion and compression the same as that of an external source and external condenser. This is no mere accidental circumstance, but depends on the nature of heat itself; so that Carnot's ideal heat-engine was a mere empty phantasy; and the mathematical elaborations of this phantasy by Kelvin and those who have followed him in this direction partake of its phantastic nature.

If we set a Carnot engine working forwards with maximum efficiency to work a similar engine backwards it is evident that the latter engine would extract heat from the condenser, but could not transfer it to the source. The temperature of expansion in presence of the condenser would be considerably below that of the condenser, so that the mechanical energy gained in this expansion would be considerably less than what was lost in the forward working. The temperature during compression in the reversed direction in the absence of the condenser would therefore have to be raised from a lower point than that to which it fell in the forward working; but in correspondence with this the temperature during expansion in the absence of the condenser would fall lower than that from which it rose during compression in the absence of the condenser in the forward action. During isothermal compression in the backward direction the temperature of the working substance would be much below the temperature of the source, and could give no heat to it. But if for the source we substituted another body at a much lower temperature, intermediate between the temperatures of expansion and compression in the reversed direction, so that heat could pass quite readily to this body, we could transfer more heat to this body than

was converted into work in the forward action; and of this heat a very large proportion would originate in the work done on the piston in isothermal expansion at the lower temperature.

Thus the engine would be pumping up much heat from the cold body to the body of intermediate temperature. It would also pump up most with the forward action at maximum efficiency, since combined leakage and loss owing to the velocity of the engine would then be at a minimum. These losses would diminish the energy left available for the backward as for the forward action, so that the reversed engine, in pumping up heat from the cold body, or in cooling it, would be working with maximum available energy.

If T were the temperature of the air during expansion in the forward working, and T_1 were the temperature of compression, the efficiency of transfer of such heat as was transferred to the body of intermediate temperature would be $\frac{T}{2(T - T_1)}$. It will be seen at once that, if T and T_1 are not very far apart, and the body of intermediate temperature is near T_1, the amount of heat transferred upwards in the reversed action is enormously greater than the heat converted into work in the forward action, and we can use a heat-

engine working forward, or the energy obtained from such an engine, to pump up far more heat than what had been converted into work, and even more than was consumed by the engine. That this must be so was pointed out in general by Kelvin; and when we alter his estimate of the maximum efficiency of a Carnot engine working forward from $\frac{T - T_1}{T}$, with T as the absolute temperature of the source and T_1 that of the condenser, to $\frac{T - T_1}{2T}$, with T as the temperature of isothermal expansion and T_1 as that of isothermal compression, we in no way invalidate his general reasoning. If we were using the reversed Carnot engine or any other reversed heat-engine, either for the purpose of refrigeration, or for pumping up heat from a lower to an intermediate temperature, Kelvin's reasoning would apply.

Kelvin thought, however, that the reversed Carnot engine would pump up the heat to the temperature of the source. In this respect his reasoning was just as fallacious as his assumption, following Carnot, that a reversible heat-engine is a possibility consistent with the fundamental assumptions of Newtonian physics. Not only would far less heat than Kelvin

thought be converted into work by the Carnot engine, and far less heat be pumped up, but the heat pumped up could only be pumped up to a much lower temperature than he thought.

There would be no net transference of heat upwards at all unless the body to which the heat was to be transferred was below the temperature of compression in the reversed direction, since the whole of the heat withdrawn from the cold body during expansion, and formed during compression would leak back through the walls into the cold body. Most of this heat would, however, pass into the body of intermediate temperature if it were only slightly warmer than the cold body; but most would leak into the walls, and thence back into the cold body, if the body of intermediate temperature were much warmer than the cold body.

CHAPTER II

INTERNAL-COMBUSTION ENGINES

Let us now consider the working of an ordinary internal-combustion engine. In this case heat is communicated very rapidly to the previously compressed working-substance through combustion occurring in it. Before the end of each cycle the actual working-substance is, however, thrown away, and a fresh quantity of working-substance (air mixed previously or afterwards with combustible matter) taken in and compressed to a suitable extent. The combustion occurs during an expansion stroke, and the heat thus developed is expended in raising and maintaining the temperature during the expansion, at the end of which the working-substance is expelled. In the next two strokes (or during the expulsion stroke with the two-stroke cycle) the new quantity of working-substance is taken in and compressed, thus completing the cycle.

A very high temperature of the working-substance is reached in the cycle; but since the specific heat of this working-substance increases

considerably with rise of temperature, the amount of heat applied is greater than what would be needed to merely raise the temperature to the same extent if the specific heat remained constant. The net work done in the cycle is also correspondingly greater, but with no difference in thermal efficiency, since heat-leakage and expansion are also correspondingly greater.

The cylinder of the engine is surrounded by a water-jacket with water flowing through it, or is directly cooled by a stream of air in small engines, so that the metal of the cylinder is kept relatively cool, and much heat escapes to the outside from the hot gas. At the end of the expansion this gas is still very hot and at considerable pressure, and escapes or is driven out violently in the next stroke. The bodily translatory energy communicated to it is not, however, converted into heat within the cylinder, but outside. In this respect the internal-combustion engine differs from the Carnot engine or from a condensing steam-engine, though the translatory energy communicated to the working-substance in the return stroke is ultimately converted into heat and lost, just as in any other form of heat-engine. Since, however, the working-substance is not compressed in the expulsion stroke, only part of the loss of mechanical energy occurs in this way. The rest

is incurred in compressing the fresh charge of working-substance; and the throwing away and renewal of the working-substance in each cycle does not avoid the loss of work which would have occurred if this throwing away and renewal had not taken place.

The gas thrown away at the end of expansion is far hotter than the jacket of water (which is itself in actual engines much hotter than the surrounding air), and at a correspondingly higher pressure. As already pointed out in the case of the Carnot engine, it would be useless, if the working-substance were not thrown away, to let the gas in expansion fall to the temperature of the condenser, and corresponding pressure, even if leakage of heat from the hot walls did not prevent this fall. When the gas is thrown away, as in an internal-combustion engine, this would be equally useless, although the cooling influence of the water-jacket during expansion prevents the leakage inwards of heat. The water-jacket also greatly diminishes the heat which has to be got rid of in compression, and so makes the equivalent of a lower temperature of compression possible. But heat which would not have been thrown away into a condenser is thrown away to the cool outside air, and this has to be made up for by the excess of heat absorbed by the fresh

charge of working-substance while it is being taken in and compressed.

Part of the heat in the hot gas at the end of expansion goes into the cylinder walls and jacket, and the rest into the air. But along with the heat goes the bodily translatory energy communicated by the piston to the hot gas during expulsion, and by the hot gas itself. This energy, also, is converted into heat in the air. As cool air is taken in from the outside it is partially warmed by the cylinder walls, and then heated up rapidly in the compression stroke, since the heat formed cannot escape quickly enough into the walls and jacket. But since the mean temperature of compression is considerably less than would have been the case if the original gas had not been thrown away, the work done during the compression is considerably less, and less heat is thrown into the jacket.

Against this saving of heat-loss we have to place any direct loss of heat to the outside when the hot gas is expelled, and the great loss of translatory energy. In the indicator diagram the first loss is represented by the fact that the expansion is cut short, and heat so thrown away which might otherwise have been available for positive work. The second loss is not represented at all on the indicator diagram;

and when the engine is running at about its optimum speed or faster this defect in the indicator diagram is very serious, and greatly exaggerates the apparent net work done by the piston, so that, if we use the indicator diagram in calculating the thermal efficiency, we obtain considerably too high a result when the engine is running fast. It is most essential to realise this, and the corresponding fallacy in the case of the steam-engine.

The pressure indicated by the indicator diagram during expulsion of the hot gas is the pressure on the walls of the cylinder, and not the pressure exerted by the piston, whereas in expansion the pressure indicated by the diagram is the actual pressure on the piston, since the work done by the piston absorbs heat from the gas. The work done by the piston on the gas during expulsion is only converted into heat outside the cylinder when escape is free and there is no "silencer." If the engine was running so fast that it was doing no net work, the indicator diagram would still show much net work.

If, now, we add the negative work which is not indicated to that which is indicated during compression, we obtain just as much negative work as if the gas had not been thrown away,

but had been compressed at a temperature reaching the same point at the end of compression as the new charge. During expulsion of the hot gas just as much energy is being communicated to it, and thence to the outside air, as if it were being compressed at the temperature mentioned, while during the intake and compression of the new charge at least as much extra heat is communicated to it as it would have retained if it had been compressed at the higher temperature mentioned. This temperature may be called the virtual temperature of compression. Thus the negative work which would have been performed if the gas had been compressed at the temperature at the end of compression of the new charge is represented in the heat communicated to the outside air, just as Carnot inferred. The indicator diagram, however, only indicates the work done in compressing and heating the new charge, and is thus particularly misleading if the engine is running at about the speed required for maximal efficiency, or faster. It is of course well known to engineers that the efficiency calculated with the help of an indicator diagram may be much less than the realised efficiency; but the difference is commonly attributed to frictional and other losses, which are thus grossly exaggerated, while

the essentially unavoidable loss is correspondingly underestimated, the difference between "indicated" and actually measured work done being taken as a reliable inverse measure of the "mechanical efficiency" of the engine.

We can thus regard the internal-combustion engine as if it were similar in principle to the Carnot engine, with the exception that the temperature of the working-substance during expansion is raised solely by the internal application of much heat, and that this heat is applied very rapidly and at all points in the working-substance, so that a very high temperature is reached in spite of the cool walls. Instead, moreover, of a condenser being applied only during compression, the water-jacket acts as a condenser during expansion also, while the external atmosphere acts as an additional condenser during the equivalent of the compression stroke. In the Carnot engine the heat-loss per cycle may also be indefinitely great, while in the internal-combustion engine this loss is limited.

It might seem that the water-jacket, though it serves the necessary purpose of preventing overheating of the lubricant and metal, must necessarily also diminish the thermal efficiency of the engine by cooling the working-substance during expansion. But it also, by preventing

communication of heat through the walls to the working-substance during the last part of expansion and the whole of expulsion and compression, correspondingly lowers the virtual temperature of compression when the engine is working with maximal thermal efficiency; and with an equal lowering of the temperatures of expansion and compression the thermal efficiency, which varies with the mean *relative* absolute temperatures of expansion and compression, is increased, not diminished. It is only with less than the optimum rate that the temperature of expansion is relatively more lowered than the virtual temperature of compression.

It might also seem that if we allowed the gas to expand until its temperature was lowered to that of the jacket, we could increase the thermal efficiency. The reason why we cannot do so is that if the engine was working in a cycle we should, just as with the Carnot engine, have to waste just as much heat in raising the virtual temperature of the air during the compression stage. If we endeavoured to surmount the difficulty by running the engine more slowly, we should be losing heat excessively in the expansion stroke. When an internal-combustion engine runs much too slowly owing to excessive resistance it simply stops, in consequence of heat

leakage. To get the best results from it its rate of doing work must have about a certain value, though within certain limits we can adjust this value by varying the proportion of fuel, or the quantity of combustible mixture, added per cycle. Apart from this we have to change the gear, thus altering the resistance and so maintaining the rate.

On what, now, does the thermal efficiency of an internal-combustion engine depend; and what are the limitations of this efficiency?

If, during expansion, the combustion of the fuel was complete, and if the whole of the heat was converted into mechanical energy during expansion, so that the temperature of the gas fell to an initial value which was that of the atmosphere; if, moreover, the expulsion of the gas and compression of the new charge could be effected so slowly that no appreciable rise of temperature occurred in either the cylinder or surrounding atmosphere, the thermal efficiency, without allowance for friction, would be the fraction expressed by $\frac{T - T_1}{T}$, when T was the mean absolute temperature at which work was done in expansion, and T_1 that of the atmosphere. If, also, the engine could withstand the shocks, the highest efficiency would be obtained if

the combustion occurred instantaneously at the beginning of a very slow expansion. This would give an extremely high temperature, since the combustion would be at constant volume, and would give the minimum of expansion for the heat applied, and consequently the minimum loss in compression.

It would, however, be quite futile to make calculations on such assumptions. In the action of a heat-engine doing net work there is, and can be, no such thing as adiabatic heating and expansion; and calculations based on their existence, and on corresponding constancy of entropy, have simply no relation to the actual world. The engine, if it survived the shock, would simply stop owing to heat-leakage, as soon as any energy originally communicated to it had run down. Time is required for the propagation of ignition through what is a disc of gas, and for completion of the chemical changes immediately following ignition. During this time and the whole subsequent slow expansion heat is leaking away through the walls.

To counteract this leakage the engine must be running fast, and this implies that in order to allow for the extra heat formed in the more rapid expulsion and compression, the virtual temperature of compression must be much above

that of the walls and jacket. Hence the relative absolute temperature at which work is done in expansion and the virtual absolute temperature of compression must be far closer together. But we have already seen in the case of the Carnot engine that even under these modified conditions at least half of the heat-energy which could be utilised if the engine were reversible must be wasted, and more than half if the engine is either running too slow or too fast. Hence the maximal thermal efficiency is only $\frac{T - T_1}{2T}$, when T and T_1 are the actual or virtual mean temperatures per unit of work done in expansion and compression, and no heat or unburnt fuel is thrown away unutilised at the end of expansion. For this reason a heat-engine, though the absolute mean temperature at which work is done in expansion were ten times higher than the virtual mean temperature at which work is done in compression, could not give a thermal efficiency, allowing for some loss in friction, as high as 45 per cent.

If we estimated the efficiency from an indicator diagram and the fuel consumption per cycle, we should obtain a fictitiously high efficiency, since the diagram does not indicate the unavoidable loss of kinetic energy owing to the bodily translatory energy communicated to the gas in expulsion.

By listening to the sound of an unsilenced internal-combustion engine we can form an idea of how important this loss of energy is. We might endeavour to correct the indicator diagram by drawing a line of isothermal compression from the point at which compression ends to the point at which it begins; but owing to the fact that the piston is travelling far faster in the middle than at the beginning or end of the stroke, the correction would be inadequate.

In the normal working of an internal-combustion engine the combustion does not occur so rapidly as to put an excessive strain on the engine if the cylinder walls and other parts are sufficiently thick or strong to withstand the very high pressure which is unavoidable. When, however, the engine is working fast enough to give its maximum thermal efficiency, the combustion is more or less incomplete. Even as much as a third of the heat capacity of the fuel is commonly wasted as carbon monoxide, etc., in a petrol engine. If, by increasing the resistance, we lowered the velocity so as to permit complete combustion, we should lose more by increased leakage than we gained by the better combustion. Just as a steam-engine loses by imperfect transmission of heat from the furnace, so an internal-combustion engine loses by imperfect combustion.

It also loses through the combustion not occurring early enough in the cycle. Owing to this fact the gas is still much too hot at the conclusion of expansion, and heat which might otherwise have been utilised in expansive working is thrown away to the outside. On the other hand, the horse-power of the engine is increased, just as is the horse-power of a steam-engine when steam is allowed to enter the cylinder during a large part of the expansion stroke.

It is of advantage in securing sufficiently rapid combustion that the temperature of the mixture of air and fuel should be as high as possible without causing premature ignition (or the partial detonating combustion which causes "pinking") if they are compressed together, and sufficiently concentrated to yield great power in each expansion stroke, so giving as much time as possible for satisfactory combustion with a given consumption of fuel. In engines where the air is compressed before the fuel is added there is no limitation to the concentration before ignition, and the latter is brought about in the Diesel type by the rise in temperature of the compressed air. In engines where volatile fuel is mixed with the air before compressing, the compression must be limited owing to the risk of premature ignition or "pinking." In consequence of this limitation the

thermal efficiency is considerably less high. An ordinary petrol engine is comparatively wasteful of the very expensive fuel which it uses.

It is also apt to be run in a somewhat unnecessarily wasteful manner, since by diminishing the proportion of air to petrol we can at first obtain greater horse-power at the expense of lower thermal efficiency and greater waste of unburnt gas in the exhaust. This is illustrated by the accompanying graph (Fig. 2) from an investigation by O. C. Berry.[1] It will be seen that as the proportion of petrol increases the horse-power increases after the thermal efficiency has diminished considerably, the rate of revolution being kept constant.

The graph also illustrates how low the thermal efficiency is, as compared with that obtainable with a high-compression internal-combustion engine. The efficiency was determined with a brake-dynamometer. It would have appeared much higher had it been fallaciously estimated from indicator diagrams. With the richer petrol mixtures the proportion of unburnt carbon monoxide, etc., in the exhaust gas increases considerably.

The thermal efficiency attained under favour-

[1] O. C. Berry, *Journ. Soc. of Automob. Engineers*, v., p. 364, 1919.

able conditions in simple internal-combustion engines of the types giving the highest thermal efficiencies (engines working on the Diesel principle with high compressions) is about 35 per

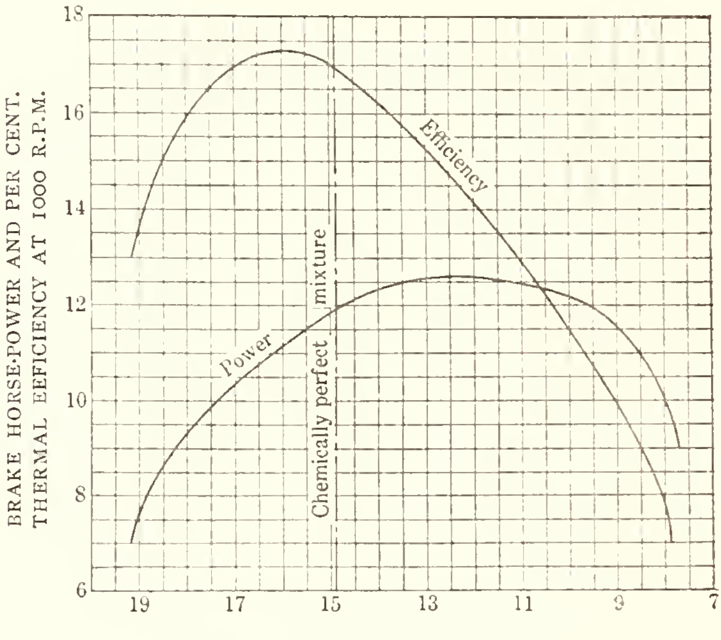

FIG. 2.—Curves showing relation of air to petrol ratio in pounds, to power and thermal efficiency of $4\frac{1}{8}$ inch bore by $4\frac{1}{2}$ inch stroke Willis-Knight 4-cylinder motor at 1000 revolutions per minute.

cent. of the "net" energy-value of the fuel, or 33 per cent. of the gross or total energy-value. It seems significant that the percentage has scarcely been improved upon for many years. A very definitely higher thermal efficiency (up to fully 40 per cent.) can, however, be attained by

utilising heat from the exhaust gas and jacket-water in generating steam, which is applied (as first proposed by Still) to help the engine on.

It appears that in order to obtain ignition and a satisfactory rate of combustion the temperature of the working-substance has to be kept higher in both the compression and expansion strokes than is consistent with what would otherwise be maximal thermal efficiency. Heat is also thrown away prematurely at the end of expansion. Thus heat is available in the exhaust gas and water for generating steam. If the engine could be worked in such a way that the waste heat could be taken up by the jacket-water at very little above the atmospheric temperature, and the exhaust gas could be discharged at the virtual temperature, before it is shot out, of compression, no heat would be available for generation of steam, and the thermal efficiency would be as high as that of the Still engine. The gas during discharge from the cylinder would be quite cool, owing to conversion of heat into energy of translation, and the temperature of the water from the jacket would be similarly low. It seems impossible, however, to obtain with a simple high-compression internal-combustion engine the advantages of the method of ignition, rapid

combustion, and high heat-concentration of the burning mixture, along with the maximal thermal efficiency of which the engine would be capable apart from its excess waste of heat.

The reason for the great advantage of a high compression ratio is twofold. In the first place, the high temperature of the working-substance when ignition occurs hastens greatly the rate of combustion, so that it is mostly over in the first part of the expansion stroke and the heat can be converted much more completely into mechanical energy during the subsequent expansion. In the second place, the amount of heat in a given volume of the working-substance during expansion is so much greater that a smaller proportion leaks into the metal in a given time. This helps, also, to permit satisfactory and early combustion without there being time for loss of an excessive proportion of heat by leakage. In this connection it must be remembered that the heat-concentration in the working-substance is greater during the whole of the effective expansion stroke: for at the end of the stroke there is more heat in the gas, in correspondence with the higher pressure and higher virtual temperature of compression. In the early Lenoir gas-engine, there was no compression. The rate of combustion was so

slow, and the proportion of heat lost by leakage so excessive, that the thermal efficiency was extremely low in spite of the very high temperature reached in the interior of the burning mixture.

The maximum efficiency of a high-compression engine is, however, diminished in consequence of the virtual absolute temperature of compression and the actual absolute temperature of expansion being raised by the same arithmetical amount, so that the difference in their relative absolute temperatures is diminished. In this way, as well as owing to the temperature being still too high at the end of expansion, waste heat is available for evaporating steam in the Still engine. It is sometimes supposed that the advantages of a high compression ratio are due directly to the high temperature of expansion. In this reasoning the higher virtual temperature of compression has been forgotten.

Not merely the thermal efficiency, but also the horse-power of a heat-engine, is of the greatest practical importance. But as the thermal efficiency increases owing to a greater relative difference between the temperatures of expansion and compression, the horse-power increases also in a much higher ratio: for the greater the thermal efficiency not only is the

work per cycle greater, but the faster does the engine work without bringing the temperature of expansion too near the virtual temperature of compression. By working the engine faster than is consistent with maximal thermal efficiency, we can, however, always increase the horse-power to some extent.

The horse-power depends also on the rate of combustion: for the faster this is the faster can the engine work, provided that the temperature of the walls, and consequently the virtual temperature of compression, can be kept sufficiently low. Many of the recent improvements in internal-combustion engines have, of course, been dependent on arrangements for increase of the rate of combustion by securing greater turbulence and in other ways.

As an internal-combustion engine becomes smaller, the time required for combustion to spread throughout the charge diminishes, so that the frequency of revolution can be increased. As, moreover, the external surface diminishes less than in proportion to the diminished volume, the metal can more easily be kept cool, and direct air-cooling may suffice. The weight of metal required in the cylinder and its connections decreases also out of all proportion to the size, so that small light engines of very great power

for their weight can be built. A great disadvantage of large-sized high-compression internal-combustion engines is that, owing to the enormous pressure developed during expansion, the weight of metal needed is very great. The difficulty in keeping it and the lubricant sufficiently cool, and yet having the temperature at the end of compression sufficiently high for ignition and rapid combustion, becomes also very serious, particularly with two-stroke and double-acting engines.

CHAPTER III

RECIPROCATING STEAM-ENGINES

LET us now consider the action of steam-engines. The case of the simple reciprocating condensing engine employing saturated steam may be considered first. In this engine the steam, usually at considerable pressure, is admitted to the cylinder during the first part of the expansion stroke; the steam is then shut off and allowed to expand further and cool, doing external work all the time. At the end of the stroke the steam is expelled into the condenser in the compression stroke, together with water which has condensed, and much steam which evaporates from the walls of the cylinder, where it has condensed during expansion. In the condenser all the steam is at the same time condensed to water. This water is then pumped back into the boiler, and heated up again to whatever the boiling-point is at the existing boiler pressure. At the same time the condenser is kept free from air by a separate pump.

The steam-engine differs from a Carnot

engine or internal-combustion engine owing to the fact that during the cycle the working-substance changes its state from liquid to gas and back, and a very large proportion of the heat applied is converted into potential energy and back. During the first short stage of expansion at near the temperature and pressure of the boiler, part of the available energy passes into the metal of the cylinder as heat, through condensation upon it. Another portion is converted into mechanical energy. Meanwhile the continued passage of steam from the steam-chest and boiler is maintaining the pressure and temperature. When the steam supply is cut off the steam continues to lose energy, partly by further condensation on the walls, and partly by the doing of mechanical work. Owing partly to condensation, both on the walls and in the body of the steam, partly to expansion, and partly to fall of temperature,. the pressure falls rapidly; but the heat liberated in condensation prevents the temperature from falling as rapidly as would otherwise be the case. On continuing the expansion, however, a point is finally reached at which the temperature of the steam is lower than that of the walls; and they then begin to lose heat by evaporation from them, and thus add to the mass of steam, and if the expansion

was not interrupted would almost prevent its temperature and pressure from falling further.

When the expansion has been carried as far as is profitable the remaining steam and water is still hot and at some pressure, but on the opening of the valve to the condenser at once cools itself to the condenser temperature, together with the steam which evaporates from the hot walls during compression, by conversion of heat into bodily energy of translation. The energy of translation is converted into heat in the condenser, together with all the further translational energy communicated by the piston to the steam and water; but if the condenser is free from air, the temperature of the steam and water in the cylinder and condenser is only that of the condenser surface, and the lateral pressure is only the vapour pressure at that temperature. The heat thrown away in the condenser arises, partly from condensation of the steam remaining uncondensed at the end of expansion, partly from condensation of steam which has evaporated from the warm walls and suspended particles of condensed water during compression, and partly from the conversion into heat of energy of translation which has been imparted to the steam and condensed water by the piston during compression, and by the hot cylinder walls and

suspended particles of water as they shoot off molecules of steam. The heat of condensation is due to the conversion of potential into kinetic energy; the heat from conversion of energy of translation is additional to this.

The cycle of the engine may be stated as follows:—During the first stage, water at the temperature of the condenser is heated to that of the boiler. During the second stage, steam is being evaporated continuously from the boiler, and is passing into the cylinder, doing work on the piston, and being condensed on the walls of the cylinder and in the body of the steam. In the third stage, the steam has been cut off, but the coincident cooling cannot be continued till the condenser temperature is reached, since steam begins to be evaporated from the walls. In the fourth stage, the whole of the steam and condensed water is shot back into the condenser, and the steam is there condensed. During this stage, the pressure which the piston is overcoming is not merely that on the walls of the cylinder, but also that due to the mass of the steam and water to which the piston is imparting bodily velocity. We cannot represent the work done and undone in the cycle of a steam-engine by a pressure-volume diagram, since the diagram does not represent internal work. A Watt indi-

cator diagram only represents (and imperfectly, as will appear below) the net external work done.

Owing to the arrangement of furnace, boiler, and steam-chest, the first stage, and the evaporation in the second stage, are spread over the whole cycle; and in double-acting engines, and still more in double or triple expansion engines, a similar result is partially obtained for the other stages.

Let us now consider what happens when, by varying the resistance to the piston during expansion, we vary the rate at which the engine is running. With a very low velocity much time is afforded for condensation on the metal and corresponding loss of heat, as compared with the conversion of heat into work done in expansion. This heat in the metal is returned, in what is called the "latent" form, and as energy of translation, to the steam during the last part of expansion and the whole of compression, and is wasted in the condenser, besides such waste as occurs through escape of heat to the outside.[1] After the engine is well started, the metal takes on an approximate mean temperature midway

[1] It is often supposed that the loss of heat through the metal is greatly reduced in the triple-expansion engine. In reality there is only a distribution of the loss among the three cylinders. The loss is unavoidable, but, as will be shown below, can be greatly reduced by high pressures and sufficiently fast running.

between the mean temperature of expansion and the temperature of the condenser surface. Evaporation of steam from the walls in the last part of expansion prevents the steam from cooling itself and diminishing its mass or concentration. There is thus, owing to the existence of leakage of heat into the walls, a considerable mass of hot steam in the cylinder at the end of expansion; and the slower the expansion the sooner will this occur, since the sooner will the gain of energy in the steam from evaporation equal the loss from doing of work. The corresponding energy is all wasted in the condenser and added to the great waste from long-continued evaporation from the walls during compression and from any leakage to the outside, though, when the engine is working with maximum efficiency, the latter loss simply diminishes the loss to the condenser, the engine-room taking on part of the function of the condenser.

With the engine travelling very slowly there is very little waste of heat owing to the translational energy imparted by the piston to the steam and water during compression, but enormous waste owing to the leakage of heat into the walls: this heat being converted into potential and translational energy, which is wasted in the condenser and there converted wholly into heat.

With a high velocity, on the other hand, the proportional leakage of heat per cycle becomes small, as it is not merely directly proportional to the time, but is further diminished by the increasing proportion of heat converted into mechanical energy during expansion. When the velocity is such that the amount of heat representing the extra mechanical work during expulsion and compression equals the heat which leaks into the walls, the total proportional loss will be at a minimum; and the extra work done in expulsion and compression will be half the work done in expansion, just as with the Carnot engine.

We can thus easily see, just as in the cases of the Carnot engine and internal-combustion engine, that the maximum thermal efficiency, without allowance for frictional loss, will be reached, and will be just half that which would have been reached had there been no leakage and the velocity was very low—had, in other words, the cycle of the engine been reversible.

This maximum depends, further, not on the temperature in the boiler, but on the mean temperature per unit of work done during the whole of expansion. Owing to insufficient freedom in entry or exit of steam, insufficient expansion, or insufficient flow of water through the con-

denser, or presence in it of air, the maximum attainable efficiency may be much below that which the temperatures in the boiler and condenser would otherwise give; in which case the horse-power of the engine will be diminished in far greater proportion than the thermal efficiency, unless unutilised heat is being wasted wholesale at the end of expansion, as when the cut-off is advanced in order to obtain more power.

What, now, apart from leakage of heat, determines the thermal efficiency of a steam-engine? Is it, as in the case of the Carnot engine and internal-combustion engine, the relative drop in the mean absolute temperature at which work is done in compression as compared with expansion? That this is not so will appear below.

Of the heat applied to the water which is the working-substance, the whole of what is not wasted in leakage or in communicating energy to the working-substance in compression is applied in either doing work directly, or in diminishing the mechanical work which would otherwise have to be done in compression. A great deal of heat is converted into potential energy during the heating and the evaporation of the water; and the higher the boiler-temperature the more is converted in heating and the less in evaporation, in accordance with the diminishing latent heat

of evaporation as the boiler temperature rises. But except for what escapes by leakage or in consequence of extra negative work done in compression, the whole of this potential energy is made available, partly for doing positive work through its reconversion into heat during expansion, but mainly, through its reconversion into heat in the condenser during compression, for obviating the doing of negative external work in compression, since it keeps the temperature down to that of the condenser surface, and the pressure of the steam down to the corresponding vapour pressure. In the latter way alone it gives the steam-engine a very great compensating advantage in comparison with the internal-combustion heat-engines hitherto considered, which, though they have a far higher temperature of expansion than the steam-engine, have also a much higher virtual temperature of compression.

As now, the steam cools and condenses during its expansion, the mass of steam left diminishes continuously. Its density diminishes, according to the law discovered by Waterston,[1]

[1] The paper in which Waterston formulated this law was sent to the Royal Society in 1853, but not published, though preserved in the Manuscript Archives. It is, however, now printed among his *Collected Papers* (Oliver & Boyd, 1928). The physical significance of the law is discussed at pp. 278-285 of my book *Gases and Liquids*, 1928.

in proportion to the cube of the absolute temperature -194 C., so that if (as is not the case) this rate of diminution were continued regularly at temperatures below that of the condenser (say 20 C.), no steam at all would be left at -79 C., and no energy at all would be wasted by the engine during very slow compression, just as would occur with very slow compression and a theoretically perfect gas, if the temperature were reduced to absolute zero.

It is of course evident that the external pressure exercised by water varies out of all proportion to the variation in absolute temperature. If, however, this variation in external pressure had been a function of the absolute temperature, the thermal efficiency of a steam-engine would have been dependent on the relative drop in absolute temperature, as in the case of the Carnot engine or an internal-combustion engine. This would be the case, for instance, if the density had diminished with the cube of the absolute temperature (which we should have expected on the fundamental assumptions of Newtonian physics). Actually, however, the density of the saturated vapour of water, and consequently, when we allow for T, its pressure, is, within the temperature limits of steam-engines, a function of the absolute

temperature -194°. Hence the maximum theoretical thermal efficiency of a steam-engine with saturated steam, varies as

$$\frac{(T - 194^\circ) - (T_1 - 194^\circ)}{T - 194^\circ},$$

where T is the mean temperature at which work is done in expansion, and T_1 the temperature of the condenser surface, no heat being unnecessarily thrown away at the end of expansion.

Owing to the unavoidability of leakage of heat through the walls, and extra loss of heat owing to the velocity of compression, the maximum theoretical efficiency, without allowance for friction or other incidental losses, is only half of this, as already explained; and the actual theoretical efficiency may, with a sufficiently unsuitable rate of working, be as low as we choose to make it. But quite clearly the thermal efficiency of a steam-engine does not depend in any way on Kelvin's factor $\frac{T - T_1}{T}$. It is evident also that the thermal efficiency of a steam-engine, in so far as it is using saturated steam, increases far faster with rise in temperature of expansion than in proportion to increase in the fraction $\frac{T - T_1}{T}$.

Let us suppose that in the simple condensing

steam-engine T was 500° (227° C.), and T_1 was 293° (20° C.). The boiler pressure would be nearly forty atmospheres, or 600 lb. per square inch, and its temperature nearly 250° C. The maximum theoretical thermal efficiency would be, not $\frac{500 - 293}{2 \times 500} = 20{\cdot}7$ per cent., but $\frac{306 - 99}{2 \times 306}$ $= 34$ per cent. That is to say, the theoretical maximal thermal efficiency would be about as high as the actual efficiency of a simple Diesel engine. This maximal efficiency would, moreover, be 85 per cent. of the theoretical efficiency calculated on the doubly wrong assumption that it is $\frac{T - T_1}{T}$. If T was only 91° C. (corresponding to a boiler temperature of 100° C.) the maximum theoretical efficiency would still be $\frac{170 - 99}{2 \times 170}$ $= 21$ per cent., and not $\frac{364 - 293}{2 \times 364} = 9{\cdot}5$ per cent. If we could get the condenser temperature down to 0° C. the maximum theoretical efficiency would be increased from 21 to 27 per cent.; and this example illustrates the great importance of a low condenser temperature with steam at low pressure. Why we cannot even approximately realise these theoretical efficiencies with a reciprocating engine, though we might, allowing for

unavoidable incidental losses, with a turbine, will be explained below.

It is, of course, evident that T, in the sense specified, is not the temperature in either the boiler or the steam in the first stage of expansion, but a lower temperature, since part of the work during expansion is done with the steam at a lower temperature. The indicator diagram of a steam-engine makes it appear as if a large part of the net work of the cycle was done at a considerably lower temperature. But this, particularly when the engine is running at about or over its optimum velocity, is only because the indicator diagram does not indicate the work done by the piston in imparting bodily velocity to the working-substance, nor that done by the heat of the residual steam and the walls in the same manner. If, indeed, the engine was given no external work to do, and was allowed to run away, it might, if the steam-supply could be free enough, still give an indicator diagram showing apparently that it was doing maximal net work per cycle, though actually it was doing no net work at all, since the mean pressure on the piston in compression would be almost equal to the mean pressure in expansion.

The actual proportion of net work done, if the engine is working at maximal efficiency, with

a smaller difference in temperature than that between the steam during the first part of expansion and the steam during compression, is not very large; and almost all of it is done with more than half the difference in temperature between the steam in expansion and in compression. The sharp fall in pressure during the second stage of expansion is due largely to condensation of steam, and not merely to fall in temperature and to expansion. Hence the value of $(T - 194) - (T_1 - 194^\circ)$ does not appear to be more than 10 per cent. below that for the first stage of expansion; and if admission of steam to the cylinder can be sufficiently free, the latter temperature will be nearly equal to the boiler temperature.

The idea that part of the heat which appears in the condenser should be due to the bodily translational energy of the steam entering it is not very familiar. We can perhaps realise it better if we reflect that if we have water boiling at 100, and steam from it passing rapidly into a strong watery solution, we can raise the temperature of this solution to its own higher boiling-point, though the temperature of the steam itself is only 100. We can also use the linear translational velocity of steam to drive cold water into a boiler, as with the Giffard injector. The mere

fact that the temperature in the condenser has a certain value is no evidence with respect to the thermal efficiency. An engine which, because it was running either too slow or too fast, was grossly inefficient would still have the same temperature in the condenser as if it were running efficiently.

The following experiments illustrate the manner in which the heat of steam is converted into energy of bodily translation, and also the importance of having a good air-vacuum in the condenser.

Part of the steam from a flask A of boiling water (Fig. 3) is allowed to pass into another stout flask B kept immersed in a bath through which a stream of cold water runs. Previously to the experiment this flask is evacuated through the junction-tube C, which is also connected with a mercury-gauge to show the vacuum. The flow of steam is controlled by a screw-clip D, and two thermometers are inserted as shown, to indicate the temperatures of the expanded steam flowing into the flask B, and the interior of the flask itself. Another thermometer, not shown, gives the temperature of the water in the bath.

When the screw-clip is partially opened so as to allow steam to pass, it will be found, if the air-vacuum is good, that at the screw-clip the

temperature drops to that of the flask B and of the water in the bath. Thus the extra heat in the steam has been converted completely, during its expansion at the clip, into energy of bodily translation. No heat can disappear in any other

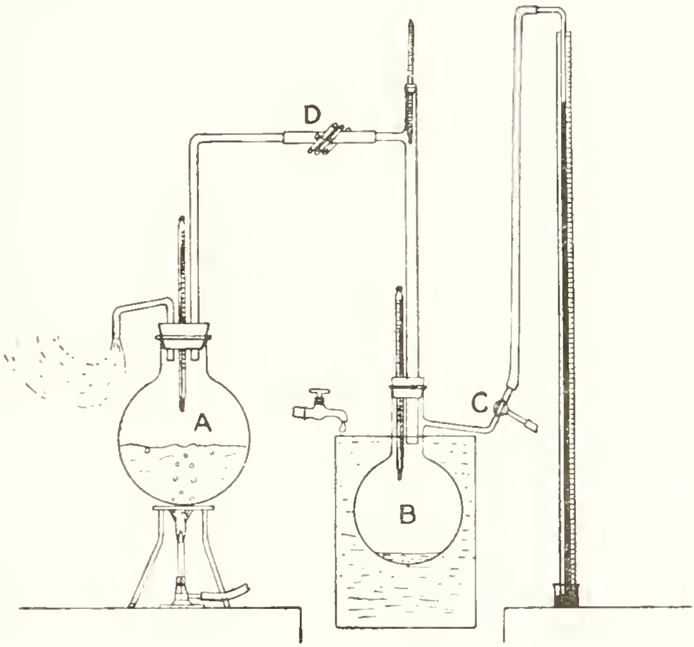

FIG. 3.

way. None can, for instance, be lost in friction, as it is reconverted at once into energy of translation; and any leakage of heat to the outside can be practically prevented, or would be compensated for by increased flow of steam from the flask A.

The same apparatus can be used to demonstrate the great importance of having no air in

a condenser. It is only after air has been expelled very completely from the condenser flask that the two thermometers show a temperature practically the same as that of the water in the bath. If some air is left inside, or leaks in, the two thermometers rise, but especially the upper one, the condenser becoming inefficient. This is due to the fact that the air in the flask B is carried towards its internal surface by the current of moving steam, and thus blankets the surface with a non-conducting layer. If only a little steam is passing the clip, and sufficient air has been left in the condenser, the steam will drive the air down below the upper thermometer, and condense at the same time on the tube carrying the thermometer. This tube, and the thermometer itself, will then become quite hot, while the thermometer in flask B shows only about the temperature of the water in the bath, since there is a blanket of air between it and the upper thermometer. In this case the flask B has been rendered completely inefficient as a condenser, and it can be seen that practically no steam is condensing upon it.

The great importance of having what is called a good vacuum in a condenser is familiar to engineers; but the main reason of this does not seem to be generally realised. It is the air-

vacuum that is of special importance. When this is bad, the total vacuum will be very bad. If the condenser is free from air, the two thermometers only rise with the temperature of the water in the bath, and the condenser acts efficiently; while if air is present the temperature in the condenser may rise a long way higher. A difference of a few degrees in the temperature of a condenser is of small importance when steam at high pressure and temperature is being used, though of more importance, as has already been pointed out, with steam at low pressure, and particularly with a turbine, which can utilise steam of very low pressure.

To illustrate the conversion of energy of translation into heat, the condensing flask is about half-filled with brine heated to near 100°, but not placed in the cold bath. An outlet is also open to air. The steam is, by obstructing the outlet of the flask A to air, and opening the clip D, made to bubble freely through the brine, so as to keep it mixed. The temperature of the brine now rises to about 108°, although the steam itself is only at 100°. The rise of temperature is due to the conversion of energy of translation of the steam into heat. Until the boiling-point of the brine is reached, more

molecules of steam are passing into the brine than are passing out from it, so that there is an excess of translatory movement of steam into the brine, though the heat-energy in the molecules of steam may be less than that of the molecules being shot off from the brine and in the brine itself.

To demonstrate qualitatively the conversion of heat into energy of translation in air, a thermometer is placed close into a jet of compressed air at several atmospheres' pressure, supplied at the temperature of the surrounding air from a compressor. The jet passes out into a wide tube in which it loses nearly all its velocity. The thermometer in the jet shows a temperature several degrees below that in the compressed air, or in the wide tube. This effect must not be confused with what is known as the Joule-Thomson effect, shown by "imperfect" gases; and Joule and Thomson distinguish it carefully. The energy of translation is reconverted into heat in the wider tube, owing to eddying. With the compressed air at 70 lb. pressure, and a fairly strong jet, an ordinary thermometer in the jet is about 7° C. lower. With a very small thermometer or thermo-electric junction, Joule and Thomson observed as great a depression as 20° C. when compressed air at

100 lb. pressure was used. They point out, however, that the air in the jet must have been far more cooled than this, since the bulb of the thermometer is heated by friction, just as a meteor is heated by friction when it encounters the earth's atmosphere.

The apparatus shown in Fig. 3 can also be used to show the conversion of heat in air into energy of translation, if for the flask A there is substituted a metal tube heated by a burner, so that the air reaching the screw-clip D is hot. The flask B is also discarded, and direct connection established with the vacuum pump, which is kept continuously running so as to take the place of the condenser. The temperature of the air passing the screw-clip drops to that of the outside air, and is maintained at that temperature, since, though the air round the thermometer has lost much of its energy of translation, less work has been done on it than the internal work it did in expanding to the lower temperature.

If the air reaching the screw-clip is not heated, the upper thermometer shows no appreciable drop in temperature. This is because the energy of translation which the air acquires at the screw-clip is reconverted into heat before it reaches the thermometer. As much internal work has been done by the air entering the

tube carrying the thermometer as is done on this air by the translatory energy acquired at the screw-clip, so that the thermometer neither falls nor rises. This is not the case when hot air is supplied to the screw-clip; for in passing the clip more heat is converted into translatory energy owing to the higher temperature of the air supplied, than is reconverted into heat after the clip has been passed. As will be explained in the next chapter, we can utilise part of the balance of translatory energy in driving an impact turbine, just as we can utilise part of the heat of hot air or steam in driving a reciprocating engine.

Let us now suppose that the engine condenses only at 100° C., or atmospheric pressure, but is still working with saturated steam. The absolute temperature at which heat can be thrown away is now 373° instead of 293°. The maximum theoretical thermal efficiency with T at 500° will therefore be reduced to $\frac{306 - 179}{2 \times 306}$ = 20·7 per cent. But if T is only 400°, or 127° C. (corresponding to a boiler temperature of about 130°, and an excess pressure of about 1·8 atmospheres or 27 lb. per square inch), the maximum theoretical thermal efficiency will be only $\frac{206 - 179}{2 \times 206} = 6{\cdot}5$ per cent.; while, if the

engine were an efficient condensing engine the maximum theoretical thermal efficiency would be $\frac{206 - 99}{2 \times 206} = 26$ per cent., or four times as great. With T at 450° or 177° C. (corresponding to a boiler temperature of about 186° and an excess boiler pressure of 10 atmospheres or 150 lb. per square inch) the maximum theoretical efficiency would be $\frac{256 - 179}{2 \times 256} = 15$ per cent.

The case may now be considered where the steam entering the cylinder is superheated. Superheating raises the temperature of steam, but diminishes its concentration to at least a corresponding extent, so that the total energy-content, kinetic and potential, of a given volume of steam is not increased. On the other hand, the amount of water evaporated per unit of work done is diminished; and if, owing to defective boiler-design, the heat absorbed in superheating the steam cannot be utilised in heating the boiler, an increase in the amount of heat utilised must result. In addition, however, the drop in temperature in the cycle of the engine, and consequently the theoretical maximum thermal efficiency, is increased.

This increase can, since the steam is in the gaseous state during superheating, only take

place in accordance with the law, applicable to a gaseous working-substance, that the maximum theoretical thermal efficiency varies with the value of $\frac{T - T_1}{2T}$, except in so far as an appreciable amount of heat is absorbed in separating aggregated molecules in the steam. Thus the rise of temperature produced by superheating is, at the best, only equivalent to a considerably less rise in temperature of the boiler. If, however, it is deemed necessary to avoid very high pressure in the boiler, superheating becomes, or may become, a convenient method of raising the thermal efficiency, while avoiding too high a pressure. It will also diminish the steam-consumption per unit of work done.

Let us suppose, as before, that with saturated steam T is 500° absolute, or 227° C., but that the steam is superheated so as to raise T to 650° absolute, or 373° C., which is about as high as is at present practicable. The theoretical maximum thermal efficiency will now be raised to the same extent as if $\frac{T - T_1}{2T}$ were raised to $\frac{Ta - T_1}{2Ta}$, where T is the mean temperature at which the work of expansion would be done with saturated steam, and Ta the corresponding

temperature with the superheated steam. The difference between $\frac{T - T_1}{2T}$ and $\frac{Ta - T_1}{2Ta}$ is 7 per cent. Therefore the maximum theoretical thermal efficiency is increased from 34 per cent. to 41 per cent. If the theoretical maximum thermal efficiency varied only as $\frac{T - T_1}{2T}$, it would amount to only 27·5 per cent., with a realisable thermal efficiency of not more than 22 per cent.

The theoretical thermal efficiency takes no account of losses due to friction, or of heat which does not pass into the boiler from the furnace. We have seen above that the frictional losses in reciprocating engines have been grossly exaggerated owing to misunderstanding of the indicator diagram. With the engine running at the optimum speed for efficiency, it is probable that with efficient lubrication percentage frictional loss is only slight, since friction does not increase in proportion to velocity. Boiler losses can be reduced, by suitable regenerating arrangements, to about 10 per cent. under optimum conditions, and probably the combined losses from the two causes mentioned need not exceed 12·5 per cent. This would leave a thermal efficiency of about 36 per cent., but without allowance for power needed to drive air through the furnace, water through

the condenser, etc. Even if the combined deductions reached 20 per cent., we should have a theoretical efficiency of 33 per cent.

If the engine were condensing at about 100° C., or atmospheric pressure, the maximum theoretical thermal efficiency would be 20·7 per cent. with T at 500° absolute without superheating, but at 650° absolute owing to superheating would be $20{\cdot}7 + 9{\cdot}0 = 29{\cdot}7$ per cent. Making an allowance, as before, of 20 per cent. for unavoidable losses, this would give a theoretically possible thermal efficiency of 23·8 per cent.—a higher thermal efficiency than what is obtained in ordinary petrol engines. The practically unavoidable losses in locomotive and some other steam-driven engines can probably, however, hardly be reduced below a third, leaving a theoretical efficiency of 19·8 per cent. The high thermal efficiencies which appear to be obtainable by means of high boiler pressures combined with superheating from steam-engines which are without a condenser-vacuum, or condense at considerably above atmospheric temperature, are of great practical significance, since it is often impossible to obtain abundant cold water for condensers; and in locomotive engines this is totally impossible. With steam at high pressure and temperature a low condenser temperature

is not nearly so important as when the steam is at a low pressure.

It might seem that even with a value for T of only 373° (100° C.) without superheating, we could, with sufficient superheating, obtain a quite high thermal efficiency from a condensing steam-engine. Without superheating the theoretical maximum efficiency would be, if the engine condensed at 20° C., $\frac{179-99}{2 \times 179} = 22$ per cent.; and if the steam were superheated to 650° C. the theoretical maximum efficiency would be raised to $22 + 16{\cdot}8 = 38{\cdot}8$ per cent. In actual practice, however, it is necessary, if anything at all like the theoretical efficiency is to be obtained with a reciprocating engine, to increase the pressure greatly, as well as the temperature, whether superheating is used or not, but particularly with superheating.

We can understand this from the following considerations. Superheated steam, as already pointed out, is diluted steam, containing no more energy per unit volume than steam saturated at a much lower temperature. Hence if it is to realise the higher theoretical efficiency, and still more greatly increased rate of work, which correspond to the superheating, it must enter the cylinder much faster. But since, in spite

of the help of a steam-chest, the resistance to the entry of steam is, with a reciprocating engine, already much too great with even the saturated steam, to permit of the theoretical efficiency of the latter being attained, it is hopelessly too great with the dilute superheated steam, with the result that T falls far below the value which it otherwise would have had. Thus though the horse-power will be increased, and the evaporation of water diminished, the thermal efficiency may actually fall as the result of superheating low-pressure steam, since only a very small return will be obtained for the extra heat expended in the superheating. Though the lower density of the superheated steam correspondingly facilitates its passage, the resistance varies as the temperature and as the square of the velocity. The steam has also to be set into rapid motion every time the valve to the cylinder opens, though the provision of a steam-chest lessens the loss from this cause. With the steam-turbine there are no such losses if the steam-supply pipe is large enough.

The higher the pressure in the cylinder during expansion, and consequently the boiler pressure, the greater the concentration of the steam at the same temperature. The more slowly, therefore, does the temperature fall in the cylinder through

leakage of heat. Consequently the less rapidly need the engine work, and a given *volume* of steam enter, in order to give its maximum efficiency. There is thus more time for the entry of a given *mass* of steam, and consequently an increased possibility of approximating to the maximum theoretical efficiency. Just as with the internal-combustion engine we increase the thermal efficiency by increasing the compression and thus giving time for effective combustion, so we increase the efficiency of a reciprocating steam-engine by raising the pressure and thus giving time for the required entry of steam. In either case, however, the increase in thermal efficiency is limited by the theoretical maximum attainable with the pressure and temperature of the steam, or the rise in temperature of the gas. Just how much increase in steam-pressure is required to realise approximately the theoretical thermal efficiency with a reciprocating engine is not yet definitely known.

Further experimental results with sufficient piston-velocity to realise maximum efficiency are greatly needed; but in view of the striking increase in efficiency resulting from high compression in the internal-combustion engine, there is no reason to doubt that corresponding results can be obtained with high-pressure steam. In

the design of the steam-engine there is very much to be learnt from the design of the high-pressure internal-combustion engine.

The thermal efficiencies and corresponding horse-powers obtained from even condensing reciprocating steam-engines are commonly much lower than from internal-combustion reciprocating engines of the same size or weight. Let us consider the explanation of this. The explanation certainly does not lie in the smaller necessary relative difference in absolute temperature between expansion and compression. In the first place, the virtual temperature of compression is far higher in the internal-combustion engine than in the steam-engine, so that, though the actual temperature of expansion is far higher in the internal-combustion engine than in the steam-engine, this would be no very great advantage if the steam was superheated as much as the metal would stand. In the second place, however, the theoretical thermal efficiency of the steam-engine increases far more quickly with rise in the temperature of expansion than with an internal-combustion engine. This advantage renders it easily possible theoretically for the steam-engine to equal or even exceed any existing internal-combustion engine in thermal efficiency; and the high pressures obtainable in steam-engines during

each expansion, and low resistance to the piston during compression, make small double-acting steam-engines of very great power a possibility, when they are run sufficiently fast to give maximum efficiency. What, then, is the real cause of the comparatively low thermal efficiency and horse-power of existing reciprocating steam-engines?

One contributory cause is that there is always some loss of heat from the furnace and boiler of a steam-engine. With an old-fashioned boiler and engine this may amount to 40 per cent. or more of the heat furnished by the fuel, even with the engine working at its optimum rate. But with proper regenerating arrangements, modern water-tube boilers, and high-pressure steam, it can be reduced to about 10 per cent., provided that the engine is working at its optimum rate. If, moreover, the combustion of fuel can be effectively and rapidly controlled, as with oil-fuel or pulverised coal, and if, as with water-tube boilers, there is no great mass of water in the boilers, to be heated up before starting or to cool uselessly after the work, incidental losses of heat are minimised, just as with the internal-combustion engine.

As it seems to me, the main cause of the, at present common, low thermal efficiency and

horse-power of reciprocating steam-engines is not mere low temperatures of the steam, but insufficiently rapid supply of steam in the first stage of expansion. If steam from the boiler cannot enter the cylinder fast enough during the first stage of expansion to maintain the temperature and pressure at about those of the boiler while the engine is running at its optimum speed, both the optimum rate of doing net work and the optimum thermal efficiency may be reduced very greatly, and commonly are. The engine thus comes to possess to a marked extent one of the glaring defects of the Carnot engine; and its thermal efficiency and horse-power are far from what they might otherwise be, considering the temperature and degree of saturation of the steam leaving the boiler.

In the internal-combustion engine there is no choking in the supply of working-substance during expansion. The rate of supply of heat is, however, limited by the rate of combustion, which becomes quite insufficient with insufficient concentration and initial temperature of the working-substance, as already explained. Thus the early low-pressure internal-combustion engine suffered from the same defect as so many existing low-pressure reciprocating steam-engines; and the original Lenoir gas-engine, which was modelled

somewhat on the lines of the Carnot engine, except that the working-substance had to be thrown away in each cycle, had a very low thermal efficiency and horse-power.

Avoidable inadequacy in the rate of supply of steam during expansion, or, what comes to the same thing if steam-pipes from the boiler and valves on the cylinder are properly designed, inadequacy in steam-pressure, has heavily handicapped the development of the reciprocating steam-engine. Owing, on the one hand, to the survival of the academic belief that a reversible heat-engine is possible, and on the other hand, to the fact that however slowly and wastefully a steam-engine works it will still work, since the supply of heat per cycle is unlimited, grossly inefficient steam-engines with quite inadequate steam-pressures or rates of revolution continue to be in use. A convenient method of increasing the torque, and so continuing the work with still greater waste, is to continue the admission of steam over most of the expansion stroke. In the internal-combustion engine, however, the heat supply per cycle is limited; and if the engine is running too slowly it simply stops, owing to leakage away of the heat before it has time to convert itself into an appreciable amount of mechanical energy during expansion.

Without sufficient compression its power is also trifling, since so great a proportion of the heat has time to leak away during the expansion, or with faster working so much of the heat, together with unburnt fuel, is thrown away at the end of expansion. These defects were more or less evident to practical engineers, and the proper steps for correcting them were pretty soon taken, so that the internal-combustion engine shot ahead of the steam-engine. The fact that a steam-engine can, up to a certain limit of resistance, still work slowly, however much heat it is wasting, and that, owing to the survival of the conceptions of Carnot and Kelvin with regard to thermal efficiency, the waste was not evident, has delayed the corresponding development of the steam-engine, and left the reciprocating steam-engine almost stranded as regards many of its possible applications.

It seems evident from what has been said that the future of the reciprocating steam-engine lies in high-pressure steam, with its direct influence supplemented by superheating, though superheating is useless without high pressure. Neither high pressure nor superheating will, however, avail without sufficient piston-velocity. Even a steam-engine which condenses at boiling-point without a condenser-vacuum appears to

be capable, with sufficient boiler pressure and superheating, of giving a thermal efficiency greater than that of an ordinary petrol engine. The steam-engine can also be worked with coal, the heat from which commonly costs about a tenth of that from petrol. We must always remember, however, that high pressures and temperatures will be useless unless the engine is working sufficiently fast to take advantage of them; and this is just as true for a triple-expansion engine as for a simple engine.

In the non-condensing engine still so largely used the heat in the condensed water is thrown away. This represents a loss of about a seventh in the heat available for work. Only a small part of this loss is covered by using the steam-blast for blowing up the furnace, and the puffing is not only noisy, but the violent intermittent blast carries burning coal into the smoke-box and to the outside, thus causing much waste and public danger of fire, while the steam emitted is also a source of danger on roads in cold weather. The steam locomotive of the future will neither puff nor emit burning coal, black smoke or steam; and its thermal efficiency will be far higher than at present.

CHAPTER IV

THE STEAM-TURBINE AND REFRIGERATING ENGINES

THE development of the steam-turbine by Sir Charles Parsons, and its application for generating electric currrent and for ship propulsion, has rendered the steam-turbine supreme where a very large amount of power has to be generated continuously at one point. The essential principle of the steam-turbine is that power is obtained from it by means of alternate rotating and stationary blades, set with suitable curvature, from steam in which heat-energy and potential energy have been converted into energy of bodily movement in a passage through narrow openings. In these it expands and so acquires bodily velocity, either relative to surrounding objects, or to the blades themselves if they carry the openings. If the blades forming the openings are fixed, so that the jets impinge on the moving blades, the turbine is known as an impulse turbine. If the blades forming the openings are moving, the turbine is known as a reaction turbine. Evidently, however, the principle is the same whether the

velocity acquired in the openings is relative to the moving blades, as in the reaction turbine, or to surrounding objects, as in the impulse turbine.

To avoid the necessity for excessive velocity of the blades, Sir Charles Parsons introduced the principle of compounding them, in the sense that both the energy of bodily movement and the heat-energy are taken up in successive rings of moving blades, interposed between which are stationary rings of blades so curved as to turn the steam back into the right direction and to form jets.

In the ordinary Parsons type of turbine the impact and reaction principles are applied simultaneously and progressively at successive rings of fixed and stationary blades, so that the temperature and pressure fall by degrees from one end to the other of the turbine. The fixed blades as well as the moving blades are so arranged as to provide narrowed openings. The rings become wider and wider, and the openings therefore more free, in correspondence with the expansion of the steam as it passes onwards. By this arrangement an enormous amount of power can be obtained continuously and quite evenly from a single turbine, without the blades in the final ring having to move dangerously fast

in order to realise maximum efficiency. With high-pressure steam there are nearly always, however, separate high-pressure, intermediate, and low-pressure turbines.

Heat tends to leak through the metal from each ring to the succeeding one, which is at a lower temperature; but this heat is simultaneously converted into energy of bodily translation, so that no loss need occur in this way; and any small amount of steam which leaks round the tips of one ring can be utilised in the next ring. Loss of heat to the outside is minimised by heat-insulation of the turbine and steam-pipe. A very large loss, however, necessarily occurs in another manner. Let us consider the impact turbine. The steam which gets through the blades cannot stand still after doing so. If it did not move on it would block the further flow till sufficient back-pressure accumulated to hinder greatly the flow, and at the same time to make the steam pass on as fast as it was issuing from the blades at the diminished rate. We can thus see that, at the best, the blades cannot absorb more than a part of the energy of bodily translation which the steam has acquired as the equivalent of the heat and potential energy with which it parted in the narrow opening. We can further see that the steam reaching the openings from the

moving blades of the impulse turbine must issue with at least such a velocity as will overcome the back-pressure which would otherwise arise beyond them. The steam must blow through the blades, and it is only the translatory energy which can be captured by them on its way through that is available for moving them against resistance.

If the resistance to the turbine is negligible the blades will slip away before the jets of steam, so that the steam will simply blow through without doing any work, and its energy of bodily translation will be wasted in the condenser. If, on the other hand, the resistance is so great that the blades can hardly move, the steam will also blow through without doing appreciable work. It is evident that most work will be done at an intermediate resistance and velocity. But the doing of this work is subject to the condition that the steam continues to issue from the blades with such a velocity that it can overcome the pressure which would otherwise arise beyond. Starting from a heavy resistance and consequent low velocity of blades, we can diminish the resistance and increase the velocity, thus taking more and more of the translational energy out of the steam, till a point is reached where the translational energy left in the issuing

steam is just sufficient to remove it onwards. At this point the translational energy left will be just equal to that taken up by the blades, since any increase in the work done on them would involve the impossible assumption that the steam was not getting away freely. The velocity can, of course, be increased further by further diminution in the resistance, but the work done on the blades per unit of steam passing can only diminish, and add to the energy wasted in the condenser; whereas until the energy wasted in blowing through the blades has become no greater than the energy taken up by the blades, increasing the velocity of the blades will increase the work done on them. To the reaction turbine these considerations apply just as much as to the impulse turbine.

We can thus see that with the turbine, just as with the reciprocating engine, half the energy available is necessarily wasted, though an indefinitely larger proportion may be wasted if the blades are travelling either too fast or too slow. In this respect also the turbine resembles the reciprocating engine. Hence with a turbine using saturated steam the maximum efficiency is $\frac{(T - 194) - (T_1 - 194)}{2\,(T - 194)}$. Since, however, steam enters the turbine continuously, and is doing its

work evenly, the value of T is that of the steam entering, and not a lower value, as with the reciprocating engine. In other words, with a given temperature and pressure in the boiler a turbine can give a higher theoretical maximum efficiency.

The work done on a steam-turbine during the passage of a given amount of steam depends upon the pressure of the steam in the direction of rotation multiplied by the distance moved. But the pressure varies as the square of the difference between the velocity in the direction of motion of the blades and that with which the steam impinges on them. It follows that when the pressure is half what it would be with the blade standing still the work done by the steam on the blades will be at a maximum. For, with further increase in velocity the pressure will fall off in a higher ratio than the velocity will increase, while, with diminishing velocity the velocity will fall off in a higher ratio than the pressure will increase. Thus if the blade-velocity were diminished from the optimum velocity by a fifth the pressure would be increased by less than a fifth; and with the velocity reduced to a hundredth the pressure would be not quite doubled. On the other hand, with the blade-velocity increased by a fifth the pressure would diminish far more than a fifth;

and, with the blade-velocity increased to that in the same direction of the steam directed on it the pressure would be zero. This blade-velocity is about twice as great as the blade-velocity which gives maximum efficiency, since the less work the steam does upon the blades, the faster does it pass through them on its way to the condenser. The translatory energy unaccounted for would pass on into the condenser; and the minimum loss to the condenser would be when the maximum work was done on the blades, and was equal to this loss, as already shown.

With the high pressure and superheat discussed in connection with the reciprocating engine, the turbines hitherto in use have not realised the thermal efficiencies which, allowing for 20 per cent. loss, might be expected of them under optimum conditions: for they have fallen somewhat short of 35 per cent. efficiency. It appears to me that probably the main cause of this is that the blades occupy so large a part of the diameter of the turbine that if the optimum speed is realised at one part of the blades this cannot be the case for other parts; and that from this cause there is considerable avoidable waste of the energy of bodily translation in the steam. The long blades add to the horse-power of the turbine,

but at the cost, not only of thermal efficiency, but also of extra size of boilers and condensers. We should have to make the turbine larger to give the same horse-power as with the longer blades; but we should save in fuel consumption and in the size of boiler and condenser.

Since a turbine can convert only half the available energy of bodily translation into mechanical energy, and since the energy of bodily translation varies as the square of the velocity, it follows that the steam, in passing through the turbine, can only lose about 29 per cent. of its velocity, since the square of 71 is about half the square of 100. In the case of a well-designed windmill freely exposed to the wind the air can lose a good deal more of its velocity in passing through the blades; but the extra velocity lost is picked up again later from the passing wind, so that the real efficiency is no greater than that of the turbine. The passing wind is, in fact, doing some of the work on the windmill.

The ultimate reason why the steam-turbine cannot convert more than half the available energy of translation into mechanical energy is that heat-energy is chaotic. We can convert added heat in the working-substance wholly into energy of bodily translation; but when we apply

this energy to the moving blades of a turbine we cannot utilise more than half of it, because in removing the working-substance heat has to be reproduced. If sufficient translational energy were not left in the working-substance to effect its removal into the condenser or elsewhere, the steam-flow would be stopped, since, owing to the chaotic movements of the molecules of steam they would get in the way.

With a water-turbine we can convert practically the whole of the translational energy of the water into mechanical energy if the turbine is running at the right speed. The water falls away from the ends of the rotating blades without waste of energy. But with a steam-turbine or gas-turbine the chaotically-moving molecules of the working-substance must retain sufficient translational energy to effect their removal, and this energy passes into the condenser or into the outside air. Thus it is the chaotic nature of heat-energy which makes it impossible to convert more than half the available heat-energy into mechanical energy, whether with a reciprocating engine or a steam-turbine.

The steam-turbine has the great advantage that power can be obtained from it continuously, smoothly, and with the maximum economy of heat which the pressure and temperature of the

steam furnished by the boiler admit of, instead of at a fluctuating rate, far less smoothly, and with less economy, as in even a double-acting or triple-expansion steam-engine, or intermittently, as in any form of internal-combustion engine. Thus the weight of metal required is greatly reduced, particularly in comparison with an internal-combustion engine; and when efficient water-tube boilers are also used, there is a further great reduction in weight and capital expenditure.

A still further great advantage in comparison with a reciprocating steam-engine is that the admission of steam is at an even rate and free. This gives the turbine a particularly great superiority with low-pressure steam. Still another advantage is that frictional loss and difficulty of lubrication are diminished, though the gain from this cause in realised thermal efficiency has been much exaggerated from the causes already discussed.

Thus both the horse-power and thermal efficiency of a steam-turbine of given weight are much greater than those of a corresponding reciprocating steam-engine with the same pressure and temperature of steam leaving the boiler, and more particularly with low-pressure steam. It seems probable also that we shall soon have steam-turbines working with at least as great

thermal efficiency as any simple internal-combustion engines, as well as with very considerable saving in capital cost and fuel cost, since the steam-engine can burn coal. In spite of the relatively high thermal efficiencies and horse-powers, and other great savings which have already been attained with the steam-turbine, there appears to be a definite prospect of considerable further advance in the same direction. On this point I am in agreement with the opinion which Sir Charles Parsons has recently expressed.

With the limitations in temperature imposed by the steel at present available, it has proved difficult to devise an internal-combustion turbine which would give a thermal efficiency at all satisfactory as compared with that of a high-compression reciprocating internal-combustion engine or a modernised reciprocating steam-engine. If only steel were used, much of the heat would have to be simply thrown away in keeping the metal cool, whereas, as we have seen, there is no waste of this sort in the reciprocating internal-combustion engine. The difficulty may perhaps be overcome, however, with the help of some fire-resisting substance. The engine would consist of a combined turbo-compressor and turbine.

The turbine has certain disadvantages which limit its general application. In the first place, it cannot be reversed, since this would require a different arrangement of blades, unlike a reciprocating engine. In the second place, if its length is kept down it has to be run so fast in order to secure maximum thermal efficiency that gearing has to be introduced in connection with many kinds of work, or else electrical drives. Failing sufficient arrangements as to this, a turbine is apt to be run too slowly to give the maximum thermal efficiency and horse-power of which it is capable with the pressure and temperature of steam available, and thus to give rather disappointing results. But the same remark applies to high-pressure reciprocating steam-engines or internal-combustion engines.

The efficiency of any form of steam-engine is of course closely connected with the adequacy and efficiency of the boiler and the proper regulation of supply of air and fuel. If we force the draught we can burn immense quantities of fuel in a furnace; but if the heating surface of the boiler is insufficient to take up the heat, most of it may be wasted. Waste of fuel will also occur if the air-supply is insufficient, and waste of heat in the flue-gases if there is too much air. In any case, much heat will be wasted

unless the heat in the hot waste gases is utilised to heat the incoming air and water.

Since water-tube boilers will safely stand very high pressures and give a minimum weight of metal and of water for their heating surface, they present very great advantages. Without the high pressures which they can give it seems to be impossible, with a reciprocating engine, to obtain a thermal efficiency at all corresponding to the pressure and temperature of the steam leaving the boiler. We must remember, however, that in order to realise the high thermal efficiency and horse-power the engine *must* run very fast, and not be too big or heavy for its work. Hence gearing or an electrical drive may often be necessary, as well as changeable gearing in small engines when the resistance is variable over long periods. We should bear in mind the fact that the so-called "elasticity" of the steam-engine, convenient as it is, has proved disastrous to its development as a thermally efficient prime mover.

Had Kelvin applied his formula $\frac{T - T_1}{T}$ to denote the ideal thermal efficiency of a steam-turbine using saturated steam, with T as the boiler temperature, and T_1 as the temperature in the condenser, his estimate would usually have

agreed fairly closely with the estimate given above. With, for instance, the value of T at 100° C. and the condenser at 20° it would have given an ideal efficiency of $\frac{373-293}{373} = 21$ per cent., without deduction for furnace and other unavoidable losses, as compared with 22 per cent. as estimated by the formula

$$\frac{(373-194)-(293-194)}{2(373-194)}.$$

A steam-engine run in the reverse direction is of course not suitable for refrigeration work, since the freezing-point of water is too high. We can, however, employ for this purpose carbon dioxide, ammonia, or various other gases which liquefy at suitable pressures and temperatures, but do not freeze at the low temperatures required. In the cases of these substances, just as with water, the variation of vapour-density with temperature, within the limits made use of, is, to judge from Waterston's data, not a function of absolute temperature, but of a much higher temperature, just as with water. If, therefore, any one of them was used in a heat-engine involving passage from the liquid to the gaseous state and back, it would give, like the steam-engine, a much higher thermal efficiency than a wholly gaseous working-substance would with

a given moderate drop in temperature in the cycle of the engine.

For a heat-engine working forwards none of these working-substances would be so convenient to use as steam; but for a reversed heat-engine-as used for refrigerating purposes, or possibly for pumping up heat from a lower to a higher temperature, any one of them can be used. To work the engine in the reversed direction the mechanical energy rendered available by working the engine forward corresponds to only half what would be available if the engine were reversible. On the other hand, this mechanical energy is probably about double of what would be available if the efficiency could be expressed as $\frac{T - T_1}{2T}$. Owing also to the ready evaporation of the liquefied working - substance, the temperature during isothermal expansion at the lower temperature in the reverse working will be equal to that of isothermal compression in the forward working. During compression in the reverse working the mean elevation of temperature at which work can be done in rejecting heat will be only half that which would exist if the engine were reversible. With a low enough temperature of rejection, however (see p. 20), the amount of heat pumped up from the source at the

lower temperature and rejected would correspond roughly to what would be rejected by a reversible engine of which the thermal efficiency corresponded to $\frac{T - T_1}{T}$, so that in the reversed direction the thermal efficiency would be $\frac{T}{T - T_1}$, T_1 being the temperature of the condenser, and and T the mean temperature at which work was done in forward expansion.

Experiments in which this was verified with close correspondence of the facts to the above theory were described in a paper read before the Institution of Electrical Engineers in December 1929 by T. G. N. Haldane. The experiments were made with an ammonia heat-pump or refrigerating plant fitted up so that heat extracted from a supply of cold water was used for heating a house by hot-water pipes, the pump being driven electrically. By this means several times as much warm water was rendered available for heating as would have been available had the electrical power been converted directly into the heat in the water. The heat wasted by a steam-turbine generating electric current could thus be compensated for if the current was used for heating, and only a very moderate rise of temperature was needed.

CHAPTER V

MUSCLES AS HEAT-ENGINES

A MUSCLE is evidently an organ of some kind which converts energy furnished by oxidation into mechanical energy. The direct connection between intake of oxygen ("nitro-aerial spirit") and muscular exertion was first pointed out by Mayow of Oxford in the seventeenth century, though much more definitely by Mayer in 1845[1]; and after Mayer's time it soon came to be no longer doubted by physiologists that oxidation of non-nitrogenous organic substances, such as sugar, furnishes the energy represented in muscular exertion.

When the molecules of chemically different substances, such as oxygen and sugar, unite with one another, they produce the chaotic form of kinetic molecular energy which we call heat; and it seems to follow that in some manner heat is converted into directed mechanical energy in muscular contraction. We can, moreover, measure easily the thermal efficiency of this

[1] Mayer, *Die organische Bewegung in ihrem Zusammenhange mit dem Stoffwechsel*, 1845.

conversion in man during the course of muscular exertion, since we can measure the extra intake of oxygen and output of carbon dioxide, etc., and thus estimate the nature and amount of the material oxidised, of which we already know, from calorimetric experiments outside the body, the heat-producing value, so that we can compare the heat energy expended with the measured mechanical work done. It appears from this comparison that the thermal efficiency with which standard kinds of mechanical work are done under the most favourable conditions amounts to about 25 per cent.

This thermal efficiency corresponds to that of a very efficient form of heat-engine. In view, however, of the current opinion that the thermal efficiency of any heat-engine varies with the drop in absolute temperature in the cycle of the engine, and the fact that in the cycle of a muscular twitch only a slight rise in temperature is found, or could exist without irreparable damage, it has been concluded by physiologists that a muscle cannot be regarded as a heat-engine; and existing ideas as to how a muscle does its work are of the haziest kinds.

Now we have already seen that the thermal efficiency of a steam-engine is much greater than in proportion to rise in the absolute

temperature at which the work in expansion is done. This arises from the fact that in the cycle of the engine the working-substance changes its state, and thus increases its pressure greatly, the change of state not occurring as a function of absolute temperature, but being quite otherwise connected with temperature. It may, therefore, be that a muscle can be regarded as a heat-engine, though the variation of temperature in the cycle of its contraction is very small.

Osmotic phenomena dependent on the existence of semi-permeable membranes, or membranes which are permeable to water, but not to various substances dissolved in it, are so prominent in the bodies of plants and animals that it at once seems very probable that muscular contraction is dependent on osmotic movements of water, accompanied by the doing of work. The pressure or turgor within protoplasm which keeps the surrounding cellulose walls distended and firm in the soft parts of plants is dependent on the concentration of dissolved molecules being very slightly greater inside the protoplasm than in the surrounding liquid, and on dissolved molecules of various kinds being unable to penetrate the membrane on the surface of the protoplasm, while water molecules can easily penetrate. When

the passage of water is resisted very great differences in pressure are produced on the two sides of such a membrane, and are said to be due to "osmotic pressure."

Thus, when a saturated cane sugar solution at o C. is separated from pure water by a membrane impermeable to sugar, but permeable to water, and the water is prevented by external pressure from entering, the pressure required to prevent the water from entering is 264 atmospheres, or about 4000 lb. per square inch, as shown by the investigations of Lord Berkeley and his associates; and, if the sugar solution increased in volume against this pressure it would overcome a resistance of nearly 4000 lb. per square inch. A muscle cannot overcome more than a minute fraction of this pressure; and it would only require a comparatively small difference in the concentration of cane-sugar per unit weight of water to give such a difference of pressure as a muscle can overcome. If, moreover, the dissolved substance were not cane-sugar, which has a very high molecular weight, but some substance, such as ordinary salt, of far lower molecular weight, the difference required in concentration by weight would be far smaller.

I have discussed, in my book *Gases and*

Liquids, 1928, the molecular mechanism of osmotic pressure, and the laws according to which it actually, as shown by experiment as well as theory, increases with diminution in molecular concentration of the solvent; and I must refer readers to this discussion. The outcome of the discussion is that in a solution the diffusion-pressure of water (or any other solvent) is necessarily diminished as compared with its diffusion pressure in pure water or a solution of lower molecular concentration of solute. Hence the water in the solution of lower molecular concentration of solute tends to diffuse into the solution of higher molecular concentration of solute through a membrane which is permeable to it. The pressure which is required to keep the water out when the membrane is impermeable to the solute molecules is the osmotic pressure; and this pressure increases and must increase, not with the mere molecular concentration of the solute molecules, as imagined by van't Hoff, but with the ratio of solute to solvent molecules. We must amend the physically meaningless conceptions and correspondingly inaccurate mathematical expressions which have been handed down from van't Hoff. To speak, for instance, of the osmotic pressure in a solution where no external pressure is applied is meaning-

less. What we mean is that the diffusion-pressure of water in the solution is so much less.

The movements within ordinary "undifferentiated protoplasm" appear to be due to transference of water from place to place in response to differences arising in the diffusion-pressure of water, owing to local differences in the total molecular concentration of the solutes present in the protoplasm, these differences being produced by metabolic changes in the protoplasm or its environment. In the case of the cells which produce the movements in sensitive plants the transference of water can be observed directly; and, as Burdon Sanderson showed, the changes of electrical potential are similar to those observed in muscular contraction. The occurrence of these electrical changes is intelligible on the osmotic theory in view of the fact that salts liberated in the protoplasm during excitation will be ionised, and that anions, as well as water, diffuse through organic membranes which are impermeable to kations. Hence differences in electrical potential will accompany osmotic interchanges where electrolytes are concerned.

In each fibril of a striated muscular fibre we can distinguish alternate transparent and opaque bands. When the fibril contracts there appears to be a transfer of liquid from the transparent to

the opaque bands, accompanied by a spreading-out laterally of both bands, so that the fibril becomes shorter and thicker. At the same time it can overcome considerable resistance to this change of form, and thus do work.

It seems reasonable to assume that the transference of liquid is a transference of water due to a sudden increase in the molecular concentration of the solute molecules, and corresponding diminution in the diffusion-pressure of water, in the opaque segments, with the consequence that water diffuses into them from the transparent segments against even a considerable pressure. But because the framework of the opaque segments resists thickening of them, they spread out laterally. After the stimulus which caused the increased molecular concentration has passed, the molecular concentration of solute molecules returns to its original state. The water consequently passes back into the transparent segments, since the molecular concentration is now higher in them than in the opaque segments, and the diffusion-pressure of water lower, the water being also driven back by the elastic pressure of the distended framework.

Since each unit of structure in the fibril is extremely minute, transfer of water will occur in

a minute fraction of a second. Osmotic transference on the laboratory scale appears to us to be a very slow process; but a simple calculation shows that on the minute scale of a muscle fibril it must be extremely rapid.

The theory that muscular contraction is an osmotic phenomenon brought about by sudden increase in molecular concentration in the dark segments was first put forward in 1909 by Professor J. S. Macdonald.[1] He pointed to various facts which support this theory, and particularly to the remarkable concentration of salts of potassium at the onset of contraction in muscle within the dark segments, seen when a suitable method of fixation has been employed.

To judge from what is known as to the liberation of heat as such during a short muscular excitation, without actual contraction, as shown by Professor A. V. Hill, part of the heat appears during the excitation, but the greater part during the subsequent stage of restitution of the original state. Hence the increased molecular concentration of solute molecules in the dark substance appears to be brought about by sudden disruption of complex molecules, with liberation of heat. The multiplication of molecules accompanying the disruption produces at once a diminution in

[1] Macdonald, *Quarterly Journal of Physiology*, 1909.

the diffusion-pressure of water, and consequent tendency for water to flow from the clear to the opaque segments, with contraction of the fibril. If, however, the contraction occurs against resistance, work is done in the process, so that heat disappears.

It was found by Fletcher and Hopkins that when muscular contraction occurs in the absence of free oxygen no carbon dioxide is formed. Thus the formation of carbon dioxide occurs in the stage of restitution, along with liberation of most of the heat. This seems to accord well with the osmotic theory, since carbon dioxide, which passes readily through semi-permeable membranes, would be useless for producing osmotic transfer of water. Since, moreover, as shown by A. V. Hill, the same amount of heat is formed in the excitation stage, whether oxygen is supplied or not, no oxygen is consumed in the excitation stage.

In a single complete twitch, heat is obtained from the disruption and subsequent recovery; but part of the heat liberated in this process must, since the temperature is raised, pass into the framework of the opaque substance, just as part of the heat applied in an ordinary heat-engine escapes. The proportion which escapes will also depend, just as in the ordinary heat-engine, on

the rate at which work is done in the contraction. The heat which leaks is ultimately carried off by the circulating blood, including heat produced during the recovery. Thus the circulating blood acts just like the condenser of an ordinary heat-engine.

When the effect of the stimulus is past, the complex molecules are re-formed, with absorption of oxygen and whatever other material is required, in addition to various inorganic or organic molecules or ions which resulted from the disruption, and, evidently, with considerable formation of heat. The water is then shot back, with relaxation of the fibril; and since no external work is done in the process, the translational energy developed is converted into a further quantity of heat, which is added to that produced in the re-formation of the complex molecules. The heat liberated by the relaxation must, however, be less than that used up in the contraction, if the latter heat has been partly converted into net mechanical energy, just as the heat produced in the compression stage of an ordinary heat-engine is less than that which is used up during the expansion.

If the muscle is prevented from shortening on excitation the opaque segments cannot expand laterally, but water can still pass into them, so

that the clear segments become thinner. This can only happen, however, against the elastic resistance of the framework, so that potential energy is stored up, to be converted into heat in the recovery stage. This heat is necessarily wasted, whether the muscle contracts or not. If the muscle contracts, the framework still exercises elastic pressure, so that potential energy is stored up, and converted into heat in relaxation. It appears, however, from the investigation of Fenn, that more heat appears when the muscle is allowed to contract than when contraction is prevented, and that most heat is produced when most work is done.

The facts demonstrated by Fenn for ordinary voluntary muscle, together with other similar facts relating to the action of the heart, may be interpreted on the osmotic theory as follows. Since the processes of breaking down of the large molecules and their resynthesis are, in the main, reversible, we may infer that on the one hand dilution of the products of breaking down will hinder, or render less complete, the process of resynthesis. On the other hand, concentration of the products of breaking down will hinder or render less complete the breaking down. In either case less heat will be liberated in the cycle, but with a certain concentration of the products

of breaking down these opposing influences will balance one another. If, however, the dilution is increased by the entry of a certain amount of water, the effect of this in hindering the re-synthesis will be less than that of the absence of the same amount of water in hindering the breaking down, since the relative dilution will be less than the relative concentration.

From this we can understand that if a muscle is prevented from contracting with a series of excitations (isometric excitation) less heat will be formed than if the muscle is allowed to contract against suitable resistance. In the former case, since the opaque bands cannot expand laterally, the products of disintegration will become so concentrated as to hinder disintegration excessively, with consequent diminution in the amount of resynthesis. When, however, the muscle is allowed to contract against a suitable resistance, so that more water can enter the opaque segments, the excessive hindrance to disintegration is absent. It is only when the muscle is allowed to contract against little or no resistance that so much water enters as to hinder resynthesis excessively. Thus the heat-production of a muscle will rise with the external work it actually does, as Fenn found, provided that the muscle is so constituted that this result

will follow. It is evidently of great advantage that voluntary muscle or heart-muscle should be thus constituted, so that we can predict this constitution in a living organism.

We can also understand on the osmotic theory why it is that a short "refractory period" follows each excitation, so that a stimulus during this period is without effect. If, moreover, we assume that the changes following excitation of a nerve-fibril are of essentially the same character as those in muscle, we can understand the heat-production, chemical, and electrical changes, although no contraction is produced.

The quicker the contraction and subsequent molecular recovery, the less time is there for leakage of heat into and from the framework of the opaque band. Hence the proportion of heat which disappears during the contraction increases correspondingly; but since the molecular recovery is also faster, the faster does it produce heat. In an isolated muscular twitch with a small resistance, a comparatively large amount of water passes from the clear to the opaque segments without more than a little work being done. Hence the driving osmotic pressure falls away greatly during the contraction; and during the contraction so little work is done that far the greater part of the heat energy lost by

the molecules is converted into potential energy, later wasted as heat, and very little into external mechanical work.

If the contraction were resisted we can imagine that in a single twitch the temperature might possibly even fall momentarily in spite of the heat produced by the sudden disruption. The working-substance in the muscle would then be taking heat from the framework during contraction, instead of losing it to the latter. In the stages of resynthesis and relaxation, however, the balance would be much more than restored, owing to heat produced in the re-formation of the complex molecules, and the conversion into heat of the translational energy imparted to the molecules of water in their return. During a continued muscular contraction the temperature of the muscle-framework would, therefore, always be above that of the environment. Since, however, the excess of elastic distension pressure producing the return would usually be small, owing to the small amount of water which had entered the opaque segments, the latter formation of heat would be small in amount.

We can always estimate, from the oxygen consumed and products of oxidation, the amount of heat-energy which is produced during the exertion; and from the mechanical work done

we can estimate the proportion of this heat which is converted into mechanical energy. There is no necessary physical connection at all between the amount of energy converted into heat and the proportion of this heat converted into mechanical energy in muscular exertion. From what we know as to the nature of life, however, we can infer with considerable confidence that the amount expended is no more than is necessary when movements producing mechanical energy are carried out. Assuming this, what are the conditions on which the thermal efficiency of a muscle, working in the manner which has been described, must depend?

An ordinary voluntary muscular contraction consists of the summed result of a series of rapidly succeeding excitations. As the result of each excitation and corresponding sudden disruption of large molecules, water passes from the clear to the opaque segments. During this passage the driving osmotic pressure will be high; but since only a little water has had time to pass in, the pressure backwards when the molecules are reconstituted will be far lower, and comparatively little water will be passing back. The muscle will thus shorten progressively, doing work against a suitably high resistance. Owing to resistance of ligaments, etc., if for

no other reason, the shortening ceases long before the full capacity of the muscle itself for shortening is reached. When, therefore, the muscle relaxes after the contraction, the deficiency of diffusion-pressure in the clear segments is much less than it was in the opaque segments during contraction. The work done in propelling the water back will also be much less than the work done in contraction. In the relaxation this work simply runs down into heat, to which may be added heat liberated in the more complete resynthesis of the complex molecules. During the contraction, however, the resynthesis, with corresponding heat-production, has been proceeding all the time.

Of the heat rendered available by the oxidation for doing work during contraction part will necessarily leak away towards the blood-stream, part will be converted into potential energy, while part will be converted into mechanical energy during the contraction; and these latter parts will be the greater the faster the work done in contraction, since less heat will leak away, the proportion varying just as in an ordinary heat-engine. But the proportion reconverted into heat in relaxation varies as the square of the velocity of retransfer of water. It follows at once, just as with any other sort of heat-

engine, that when the velocity is such that leakage comes to equal the extra loss of heat in relaxation the maximum thermal efficiency has been reached, and that this efficiency is just half what it could have been if there had been no leakage, and very slow contraction and relaxation. It should be clearly noted that during contraction the elastic framework of the opaque segments stores up potential energy, just as in an ordinary heat-engine the flywheel stores up kinetic energy during expansion.

Apart from losses of heat by leakage, and by the influence of velocity of relaxation, the thermal efficiency of a muscle working as described will depend, not on differences in temperature in the cycle of its action, but on differences in osmotic pressure. If we call Po the mean excess of osmotic pressure in the opaque segments at which work is done in contraction, and Po_1 the corresponding value in the clear segments during relaxation, then the maximum thermal efficiency, expressed as a fraction, will be $\dfrac{Po - Po_1}{2Po}$.

It is evident that this fraction may have a high value, and quite easily may even be higher than the corresponding fraction $\dfrac{T - T_1}{2T}$ in an

internal - combustion engine. The probability that the actual fraction has, under favourable conditions, a value not much lower than $\frac{1}{2}$, or 50 per cent., follows from the fact that a physiological heat-engine, or rather an assemblage of innumerable such heat-engines, is likely to waste as little heat as is possible. As already mentioned, the thermal efficiency of such muscular work as can be measured is only about 25 per cent. at the most. We have to consider, however, that this work is intermittent at short intervals corresponding to the distances over which limbs have to be moved, so that the energy expended in setting the limbs and other masses into position is not counted. Moreover, the rate at which muscles contract during, at any rate, a large part of their contraction must be a long way from the optimum rate for thermal efficiency. Hence, it can hardly be doubted, even from the mere knowledge that ordinary muscular exertion can give 25 per cent. thermal efficiency, that if we could observe muscular contraction occurring continuously and at its optimum rate we should find an extremely high efficiency, approaching the theoretical maximum of 50 per cent.

We are still at only the threshold of knowledge as to the detailed chemical changes which

occur during a muscular twitch, including the process of restitution which accompanies it. Indeed, we might almost say the same about the detailed chemical changes which accompany combustion in ordinary heat-engines, and limit in practice its rate or efficiency. No attempt, therefore, will be made here to describe how, in detail, the rapid changes in osmotic pressure which appear to cause contraction and relaxation in a muscular fibril are brought about, except to remark that liberation of inorganic constituents must play a prominent part in these changes, and are particularly fitted for doing so on account of their low molecular weight as compared with other substances to which organic membranes are impermeable. The changes in electrical potential during excitation provide a firm basis for the idea that inorganic salts participate. It must, meanwhile, suffice to have stated a coherent theory as to the general nature of the molecular mechanism by which the chaotic molecular kinetic energy, or heat, which results from oxidation, is converted into directed mechanical energy in a muscular fibril, and why so much heat is unavoidably wasted in the process.

It has been known for a very long time that, when the circulation has ceased, or acute want of oxygen in the arterial blood has been produced,

a considerable production of lactic acid ($C_3H_6O_3$) occurs in muscles and other tissues. It was also shown by Douglas and myself a few years ago that during muscular exertions (such as running quickly up a stair) which are so severe that the oxygen requirements of the muscles are far greater than the circulation can supply, there is a similar abundant formation and escape of acid, which was proved by Ryffel to be lactic acid, as we inferred at the time that it must be. During work of a more normal character, however, even when it was very prolonged, no such escape occurred; and it has quite recently been found by Owles that no escape at all occurs. As was shown by Fletcher and Hopkins, lactic acid which has been formed in muscles under asphyxial conditions (often mistaken for "fatigue") disappears when oxygen is supplied.

It has been suggested that formation of lactic acid is the essential process occurring in the normal excitatory stage of a muscular contraction, and that in the absence of oxygen the process of recovery, with resynthesis and coincident oxidation of lactic acid is arrested. It is difficult, however, to link up the mere formation of lactic acid, a substance which appears to diffuse readily throughout the body,

with the osmotic theory, or indeed any other theory, of muscular contraction. Lactic acid is apparently only one of various products of muscular excitation ; and evidence in this direction is gradually accumulating, more particularly as regards liberation of phosphoric acid.

It now seems very probable that on the failure of a sufficient supply of free oxygen from outside a muscle can produce free oxygen from its own substance by reversing part of the ordinary direction of metabolic processes. It was shown many years ago by Engelmann that the unicellular organism Arcella can not only produce free oxygen, but form bubbles of it. More recent investigations by Bles indicate that in this organism, which is peculiarly susceptible to observation, the formation of free oxygen accompanies not only shortage of externally supplied oxygen, but also ordinary prolonged protoplasmic movements. It may be that the non-formation of carbon dioxide and water, and formation of lactic acid in a muscle are simply an accompaniment of the formation of free oxygen when the normal supply is insufficient.

In the case of unstriated muscle the evident physiological function of the fibres is not to do work, but to be capable of altering their length more or less permanently. Hence the

stage of resynthesis and consequent relaxation is separated indefinitely from the stage of disintegration and contraction, both stages, however, being under nervous control. There is no reason to believe that contraction and relaxation are due to anything else but osmotic changes, though the microscopical appearances hitherto observed are insufficient to enable us to go into detail on the subject. Apparently, however, there is in the excited state an increased concentration of solute molecules in the centre of the fibre when it contracts, which leads to withdrawal of water from the ends.

It might be argued that if muscles produce their contractions in the manner which has been assumed, they cannot be regarded as heat-engines, since their action does not depend on expansion produced by heat. We must, however, regard a heat-engine as any arrangement which is of such a nature that it transforms heat into mechanical energy. Carnot's definition of a heat-engine as an arrangement in which heat is converted into mechanical power by the expansion of a working-substance at a higher temperature and its subsequent compression at a lower temperature to its original state is too narrow. It is heat-energy that a muscle transforms into mechanical energy, and nothing else,

since osmotic interchanges against resistance are produced by heat-energy. Osmotic work is not a mysterious theoretical entity, but is brought about by the battering of elastic molecules of solution against a yielding elastic resistance, in which process the molecules lose heat-energy, just as in the expansion stroke of an ordinary heat-engine.

There is, however, another standpoint from which we might criticise the treatment of muscles as heat-engines, or rather as collections of countless tiny heat-engines which normally work in unison. When a muscle is supplied with suitable fuel and with oxygen, and when it receives a suitable stimulus which we might compare to the opening of a valve in a steam-engine, or an ignition spark in a petrol-engine, it contracts and does muscular work. We can imagine a molecular arrangement which enables it to do this; but this arrangement is more or less broken down in the process. In the muscle, however, the molecular structure is straightway rebuilt from its fragments and from other surrounding molecules. Moreover in the living cells from which the muscular fibres have sprung their very peculiar structure has originally been built up, and it is constantly being renewed. We cannot picture to ourselves any sort of "engine" with

similar properties. In fact, the conception of the living muscle as an "engine" is one which does not fit our observations to more than a distinctly limited extent; and when we look carefully we find a similar misfit in respect of all other mechanical interpretations of living activities.

We might simply shut our eyes to the misfit, following the example of the mechanistic biologists of the second half of last century, and of a vast number of popular writers of the present generation. But at the present time this is no longer possible for serious students. The mechanistic biology now appears as almost childish in its disregard for observation. To interpret scientifically the biological aspects of muscular contraction we must make use of biological conceptions; and they belong to a science which is distinct from the physical sciences, since the axioms of biology are different from those of the physical sciences.

It is useful practically to regard muscles as heat-engines, just as other methods of regarding phenomena abstractly are useful for many practical purposes; but in dealing with the phenomena of life we very soon reach a point where the abstract conceptions of the physical sciences cease to be of use. The present book has dealt

with heat-engines regarded simply as molecular mechanisms, operated by nothing but what ordinarily appears to us as chaotic molecular kinetic energy constituting heat; and up to a certain point this method of regarding active muscles is of great practical service. When, however, as in physiological activities such as muscular action, we encounter a form of activity which is clearly not chaotic, but is the evident expression of organic wholeness, our physical and chemical conceptions of molecules, separation in space, energy, and the second law of thermodynamics, are no longer adequate to describe the observations; and if we do not keep our heads in presence of these observations, we are apt to relapse into incoherent vitalism on which no real scientific interpretation can be based, or else into a state of helpless nescience which is useless, since it does not help us to predict.

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